National Aeronautics and Space Administration

Advanced Manufacturing for Propulsion Systems: Additive Manufacturing, Optical Measurement, and Composites

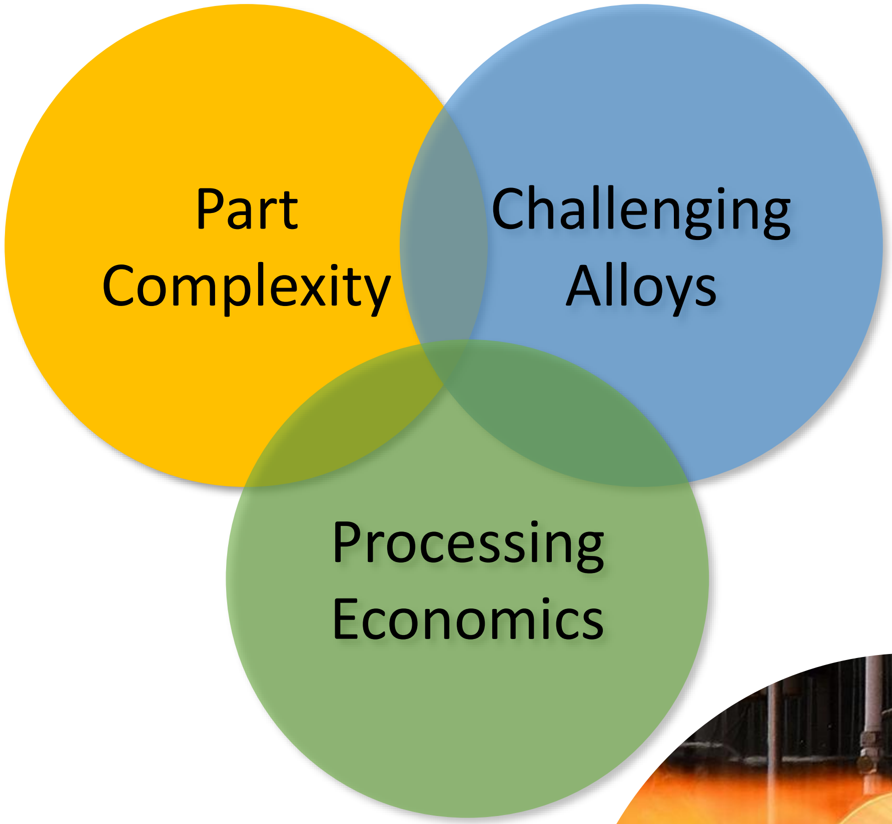
Paul Gradl

National Aeronautics and Space Administration (NASA)

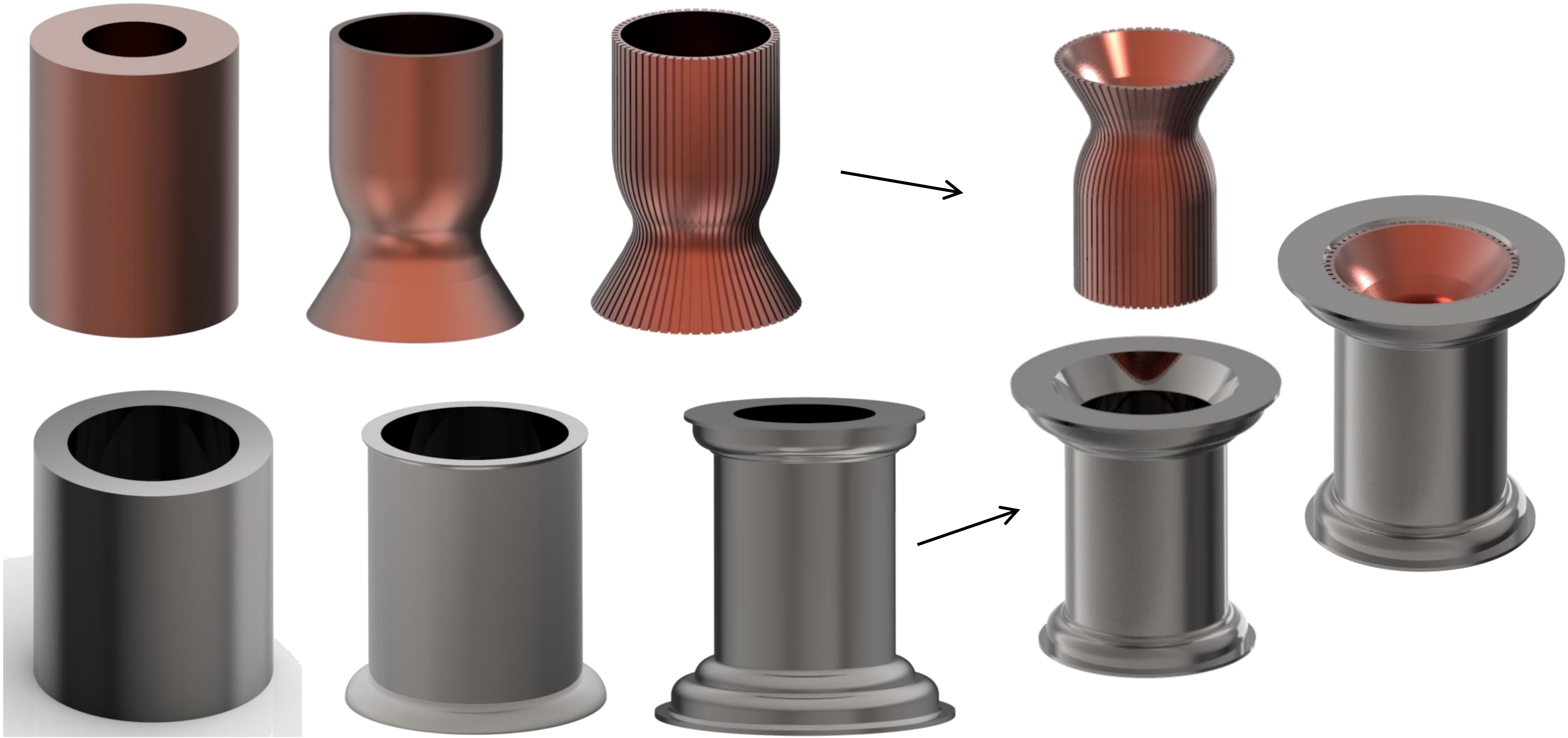
27 March 2023

The Case for Additive Manufacturing in Propulsion

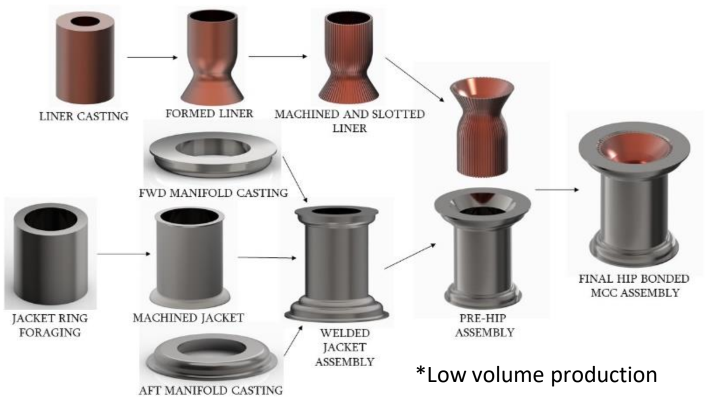
- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities.
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.



Traditional Manufacturing…Forging to final assembly



A rocket combustion chamber case study for AM

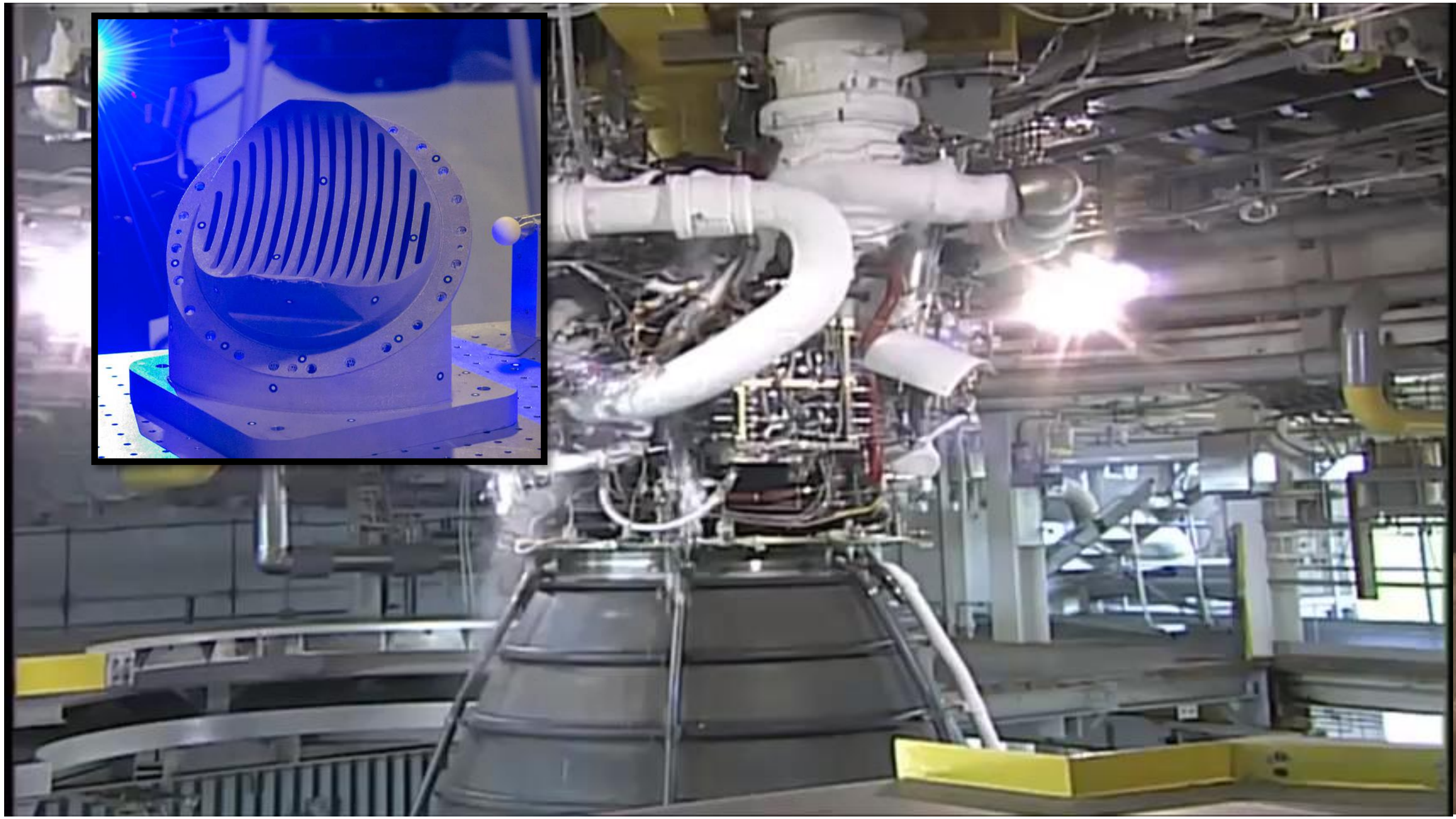


*Low volume production

Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCop-84 liner and EBW-DED Inconel 625 jacket	Three-piece assembly with AM machine size restrictions reduced and industrialized. Multi-alloy processing; one-piece L-PBF GRCop-42 liner and Inconel 625 LP-DED jacket
Schedule (Reduction)	18 months	8 months (56%)	5 months (72%)
Cost (Reduction)	$310,000	$200,000 (35%)	$125,000 (60%)

As AM process technologies evolve using multi-materials and processes, additional design and programmatic advantages are being discovered

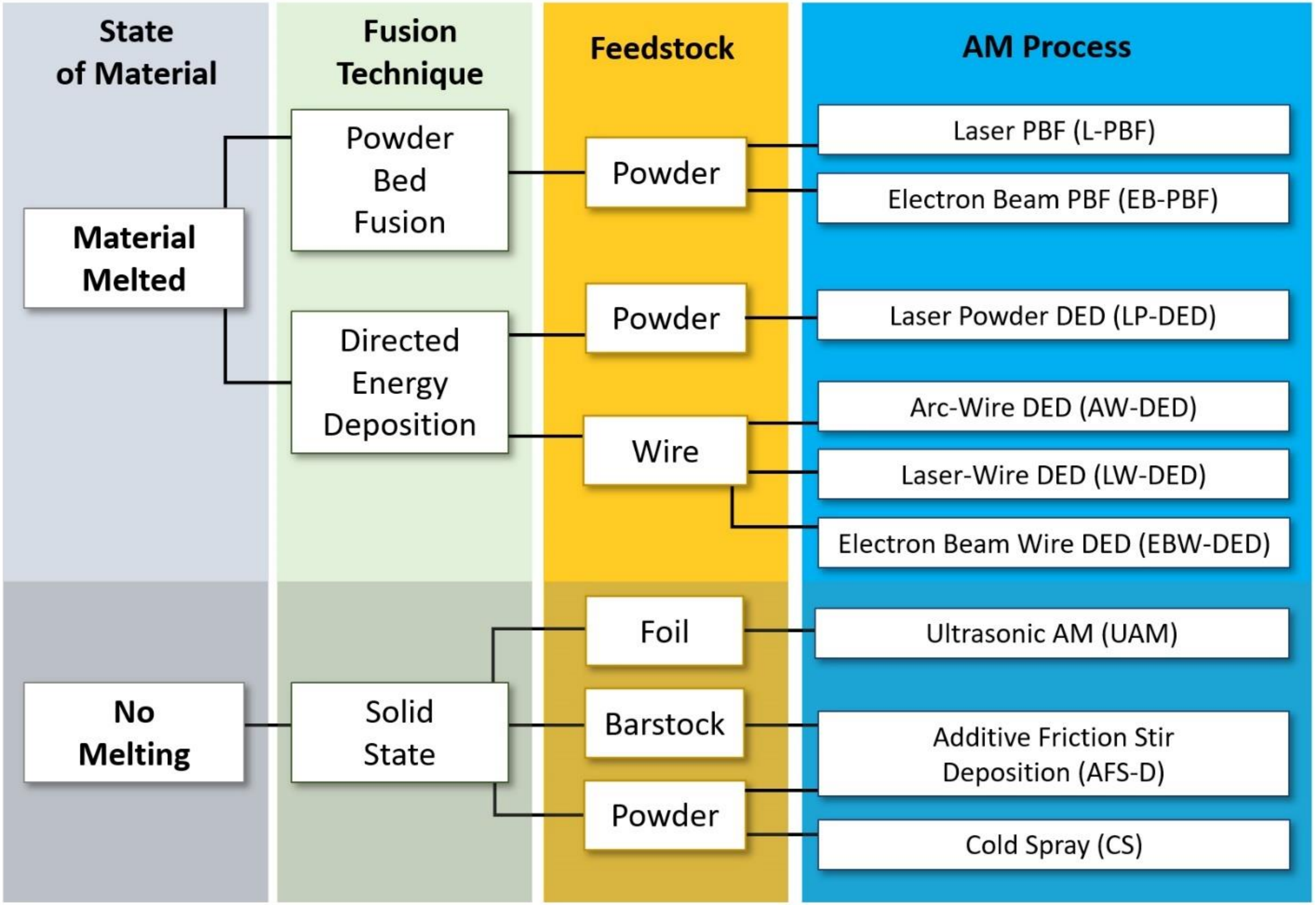
Additive Manufacturing in use on NASA Space Launch System (SLS)



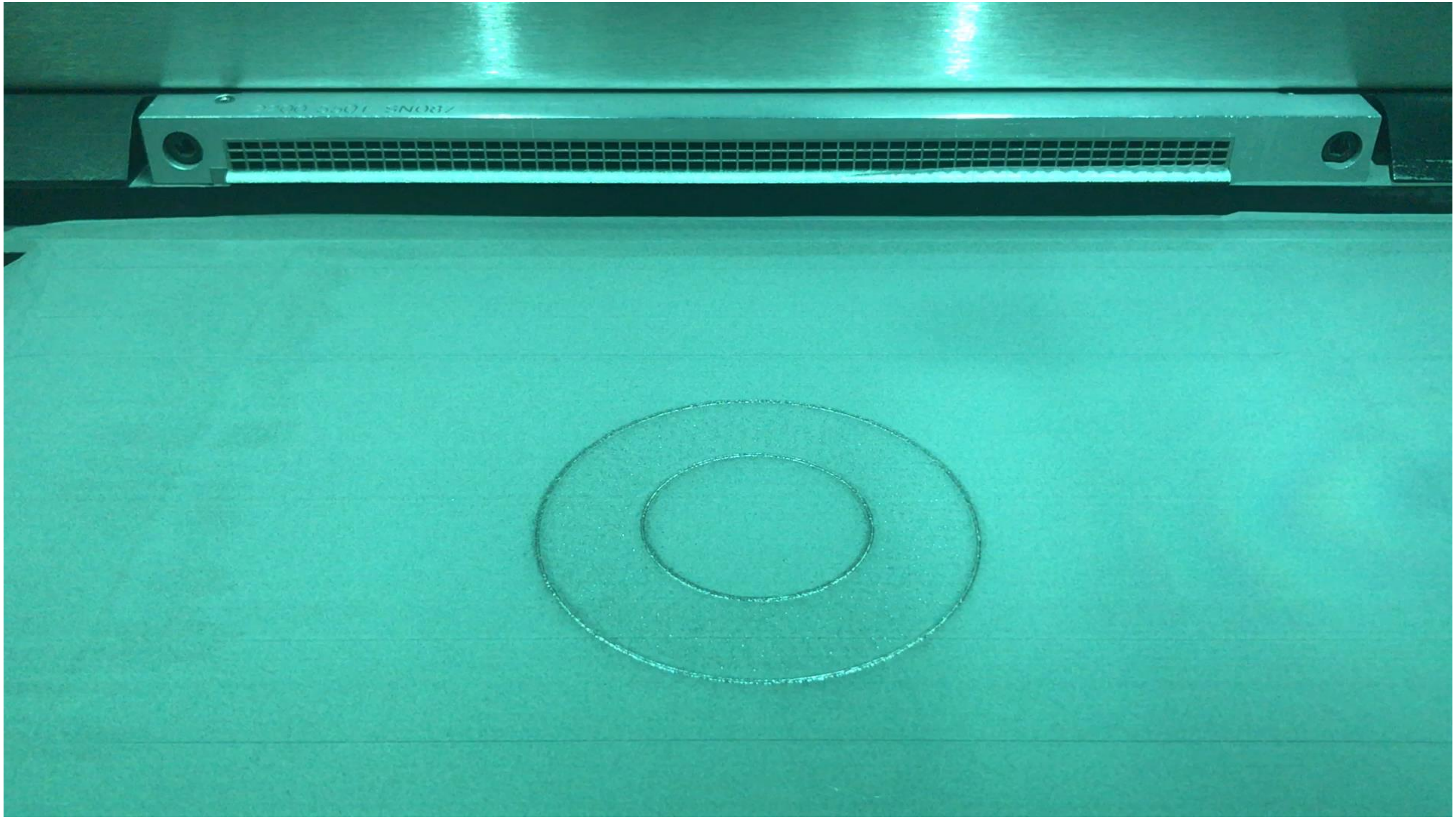
Successful hot-fire testing of full-scale additive manufacturing (AM) Part to be flown on SLS RS-25
RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from <u>127 welds to 4 welds</u>

Ref: Andy Hardin, Steve Wofford/ NASA MSFC

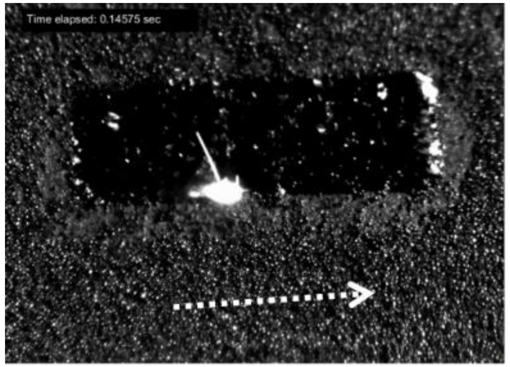
Various Metal AM Processes



Laser Powder Bed Fusion (L-PBF)

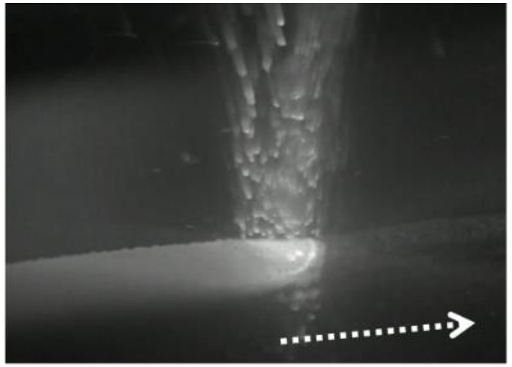


AM Processes for various applications

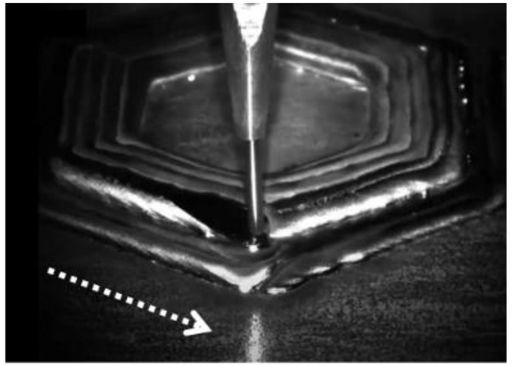


Laser Powder Bed Fusion

Electron Beam Powder Bed Fusion

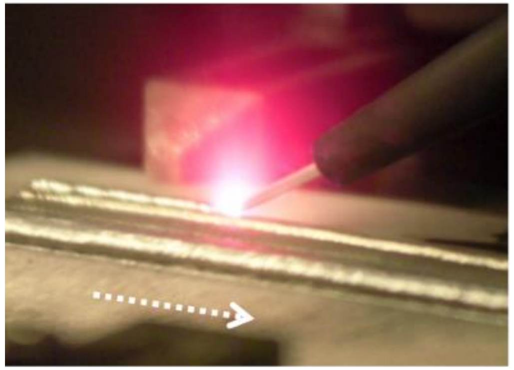


Laser Powder DED

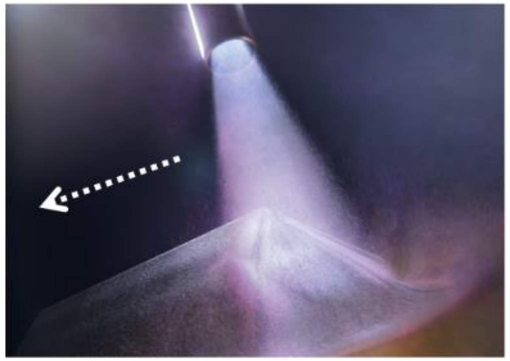


Laser Wire DED

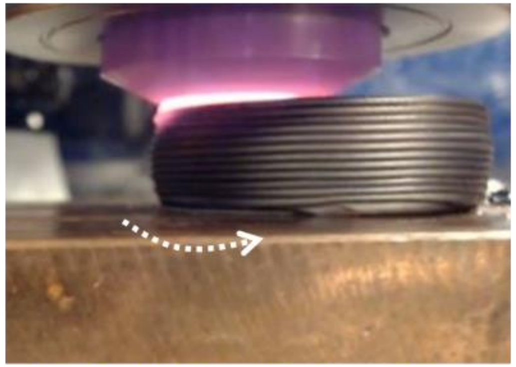
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition

Ultrasonic Additive Manufacturing

A) Laser Powder Bed Fusion [https://doi.org/10.1016/j.actamat.2017.09.051], B) Electron Beam Powder Bed Fusion *[Credit: Courtesy of Freemelt AB, Sweden],* C) Laser Powder DED *[Credit: Formalloy],* D) Laser Wire DED *[Credit: Ramlab and Cavitar],* E) Arc Wire DED *[Credit: Institut Maupertuis and Cavitar],* F) Electron Beam DED *[NASA],* G) Cold spray *[Credit: LLNL],* H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM *[Credit: Fabrisonic].*

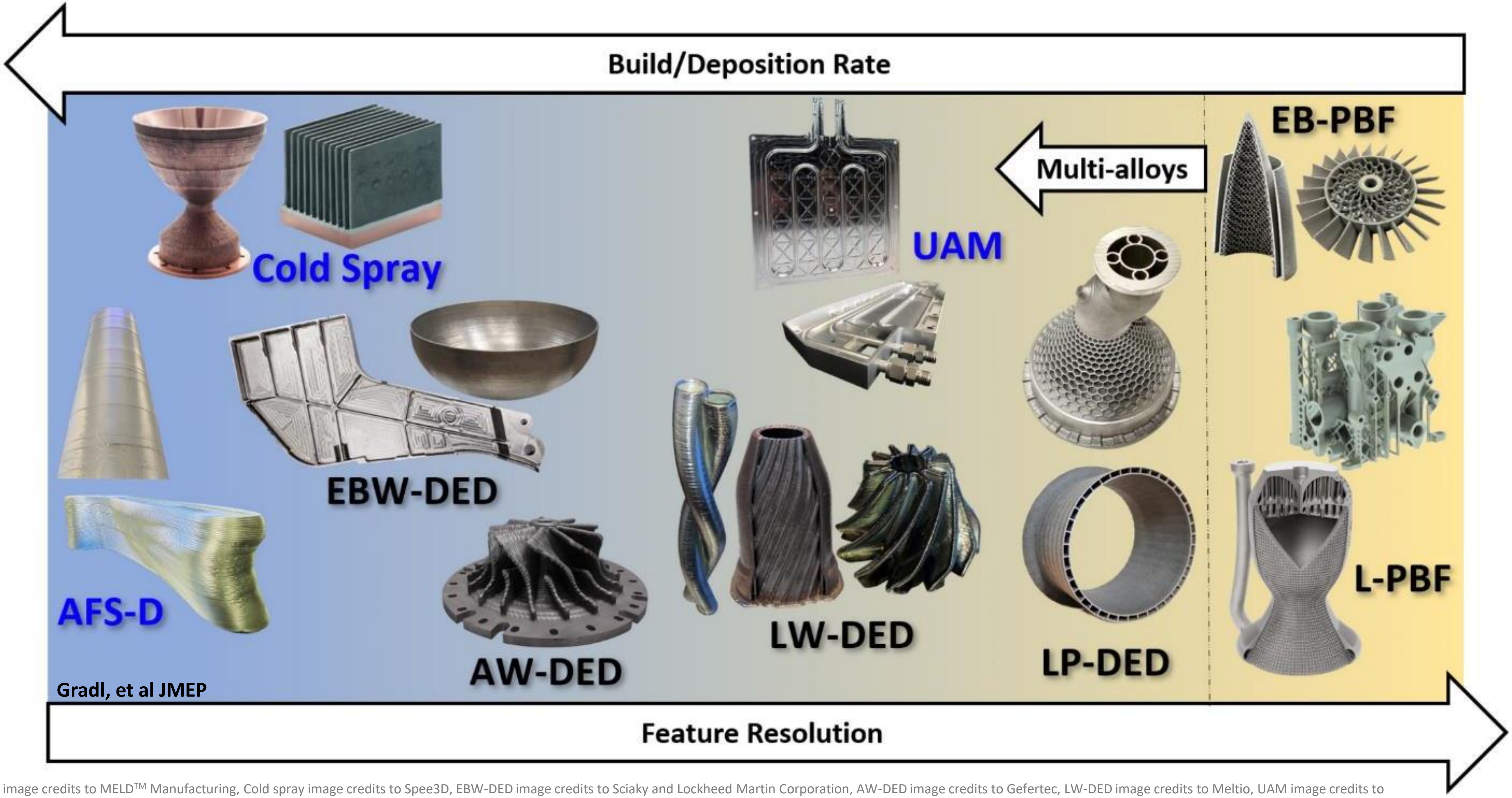
Reference: Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Methodical AM Process Selection

- What is the **alloy** required for the application?
- What is the **overall part size**?
- What is the **feature resolution** and internal **complexities**?
- Is it a **single alloy or multiple**?
- What are **programmatic requirements** such as cost, schedule, risk tolerance?
- What are the end-use environments and **properties required**?
- What is the **qualification/certification** path for the application/process?

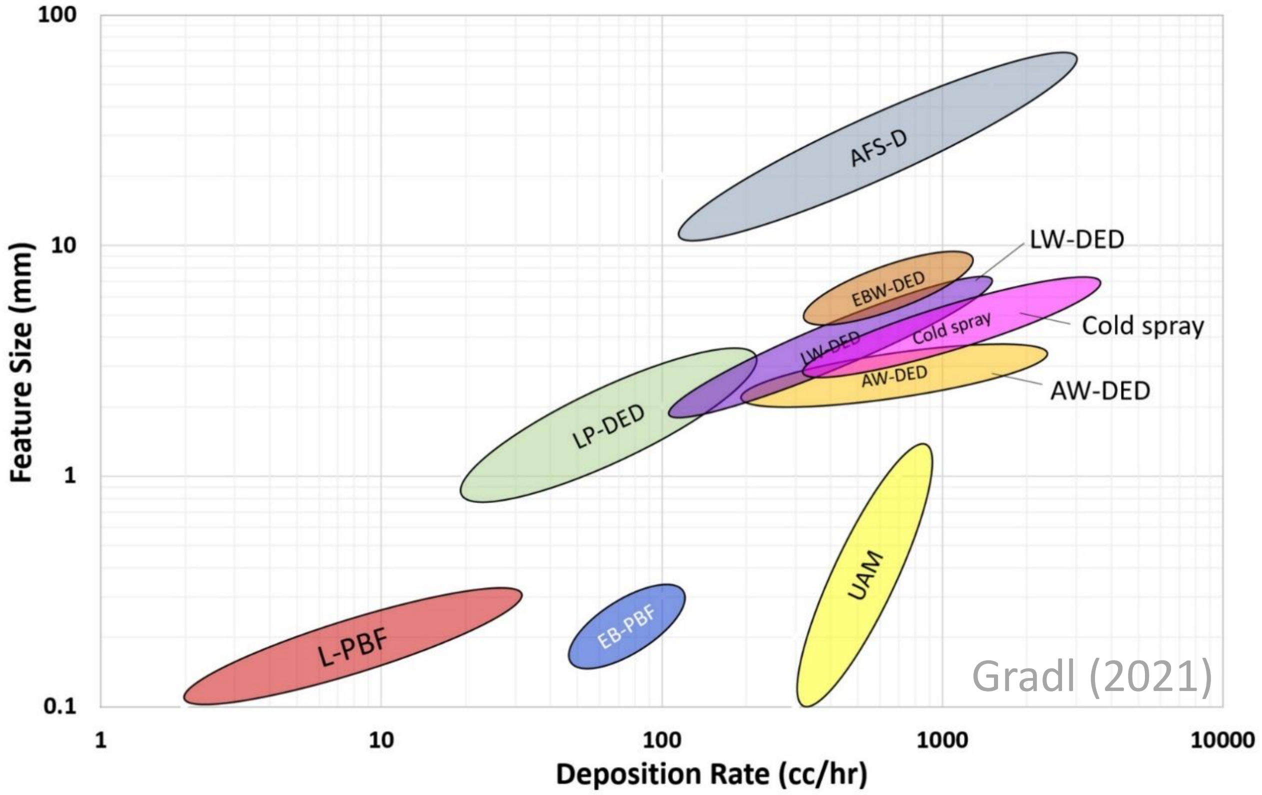
Reference: Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

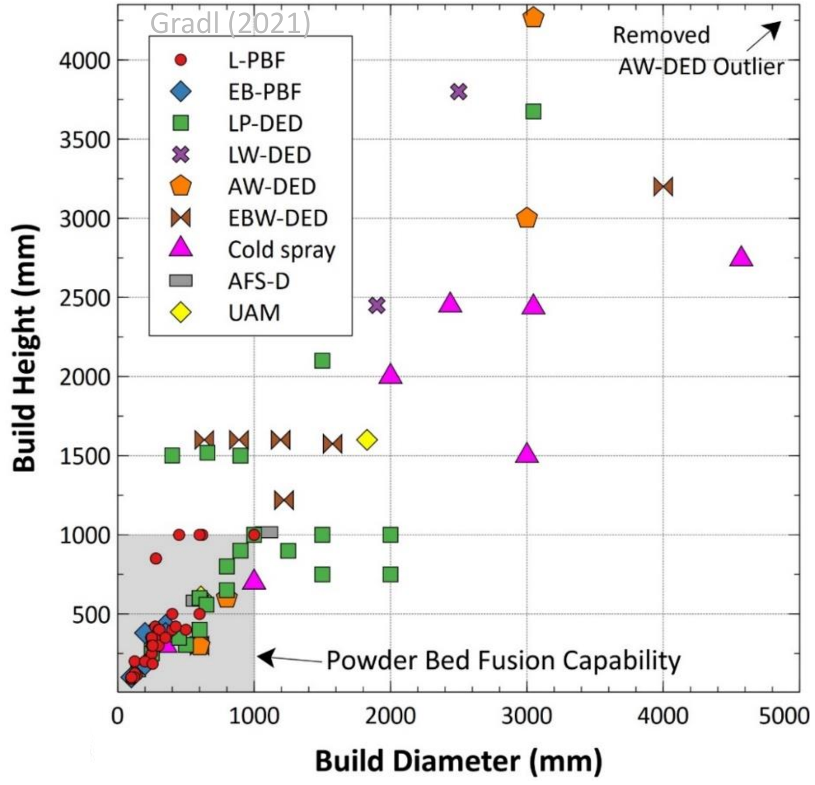
Criteria and Comparison Various Metal AM Processes



CREDITS: AFS-D image credits to MELD™ Manufacturing, Cold spray image credits to Spee3D, EBW-DED image credits to Sciaky and Lockheed Martin Corporation, AW-DED image credits to Gefertec, LW-DED image credits to Meltio, UAM image credits to Fabrisonic and NASA JPL, LP-DED image credits to DEPOZ project led by IRT Saint-Exupery and Formalloy, L-PBF image credits to Renishaw plc and CellCore GmbH/Sol Solutions Group AG, EB-PBF image credits to Wayland and GE Additive/Arcam.

Various criteria for selecting AM techniques





Complexity of Features | Scale of Hardware | Material Physics | Cost | Material Efficiency

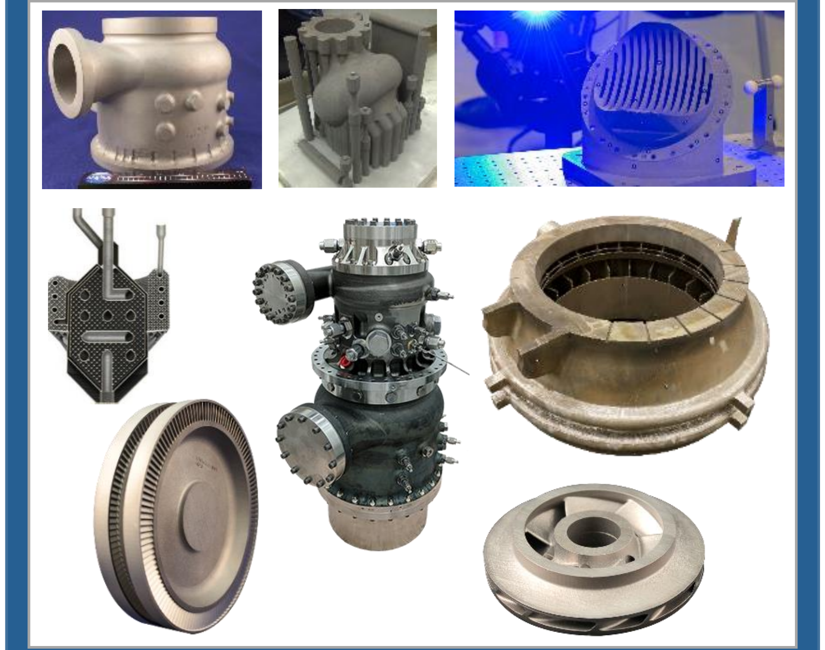
Speed of Process | Material Properties | Internal Geometry | Availability | Post Processing

Reference: Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

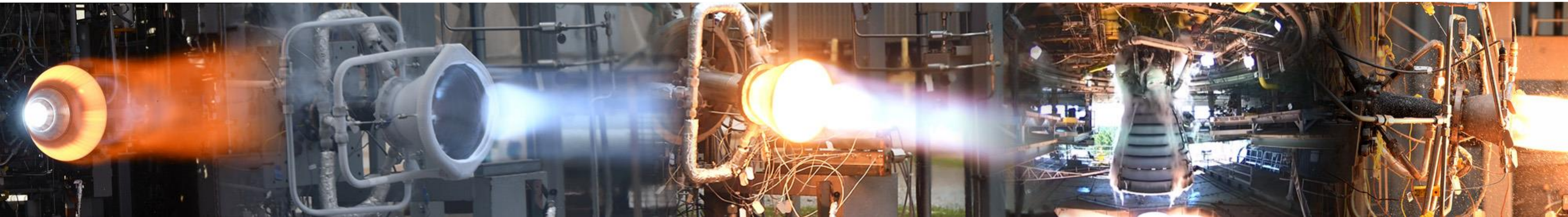
Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

Laser Powder Bed Fusion (L-PBF) Copper Alloys combined with other AM processes to provide bimetallic

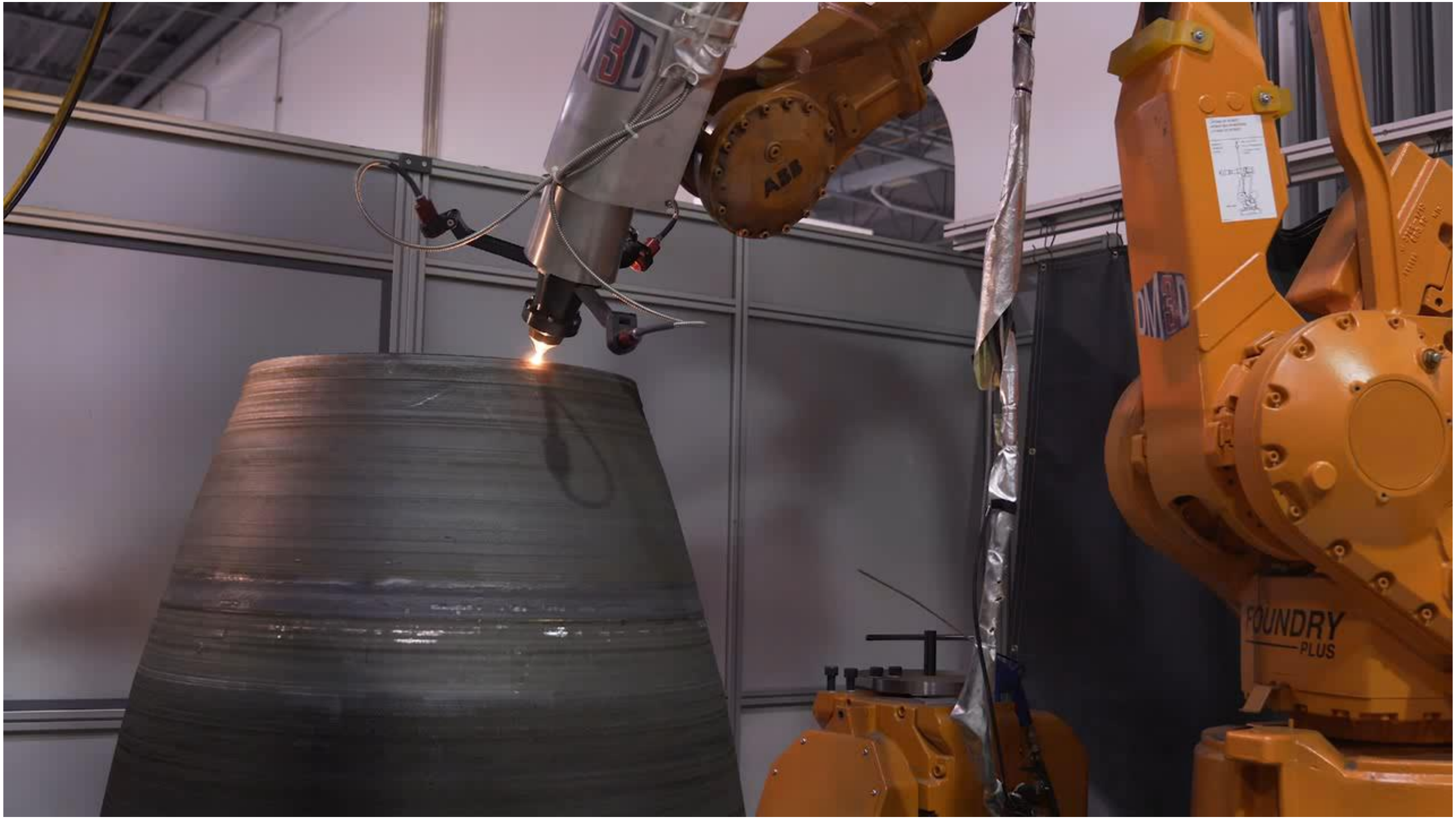
Directed Energy Deposition



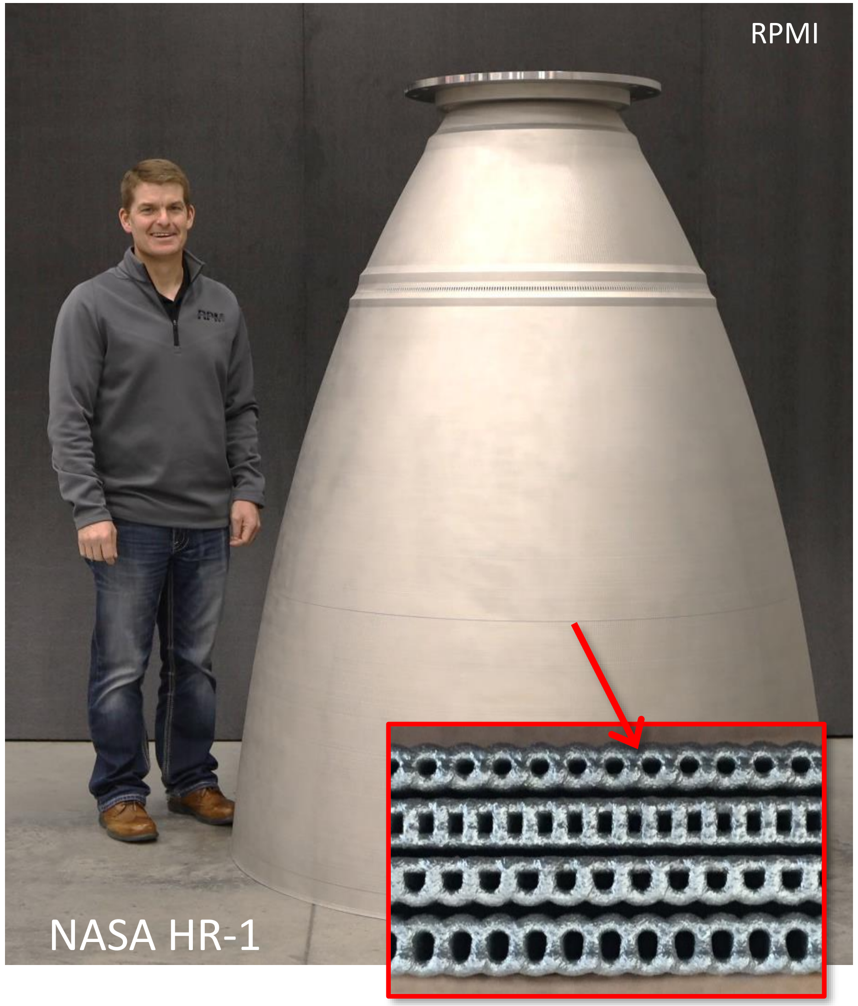
L-PBF of complex components, new alloy developments for harsh environment



Laser Powder Directed Energy Deposition (DED)



Laser Powder Directed Energy Deposition (LP-DED) Large Scale Nozzles

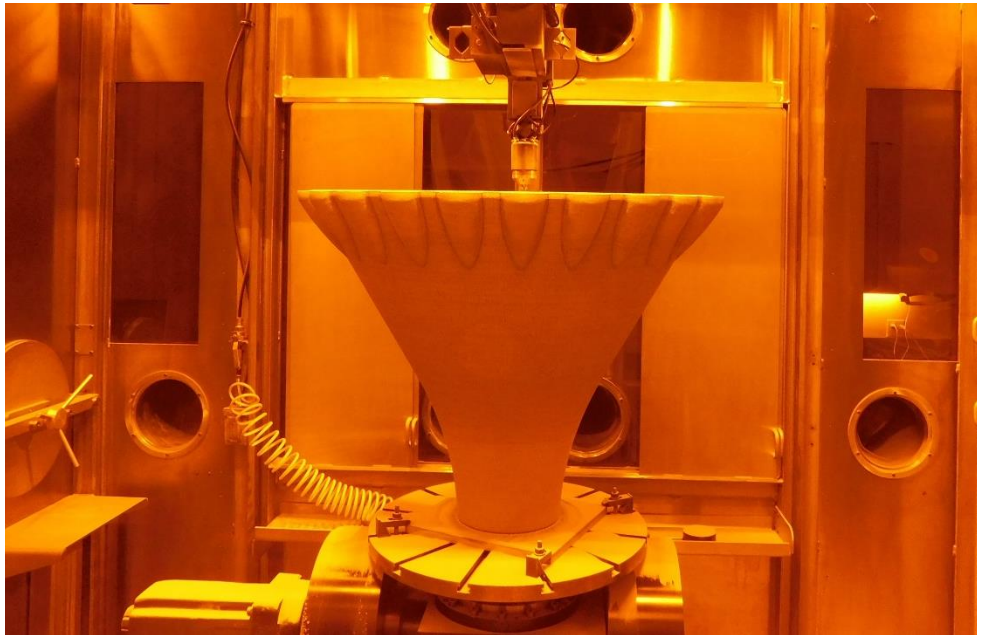


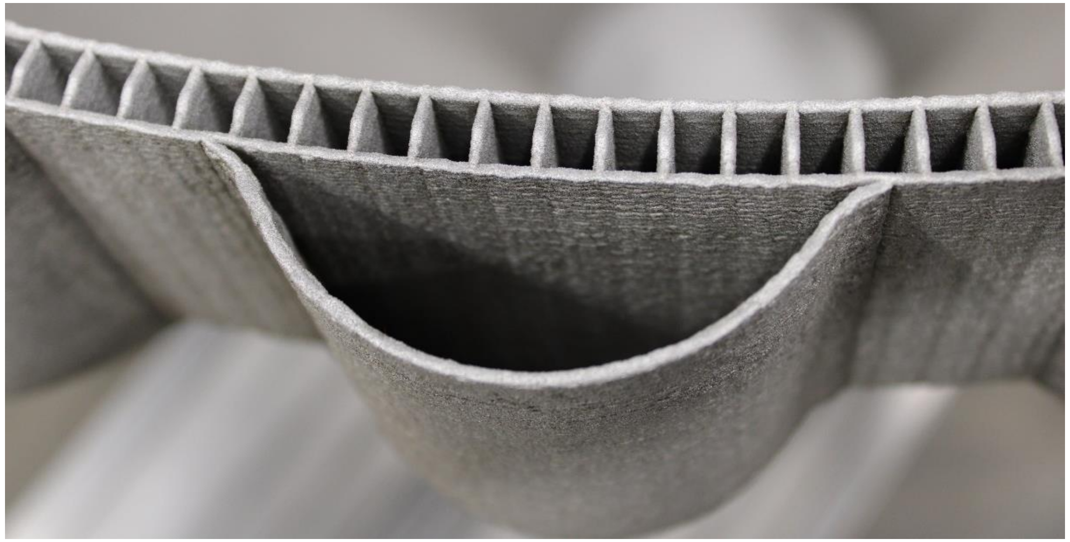
60” (1.52 m) diameter and 70” (1.78 m) height with integral channels
90 day deposition

95” (2.41 m) dia and 111” (2.82 m) height
Near Net Shape Forging Replacement

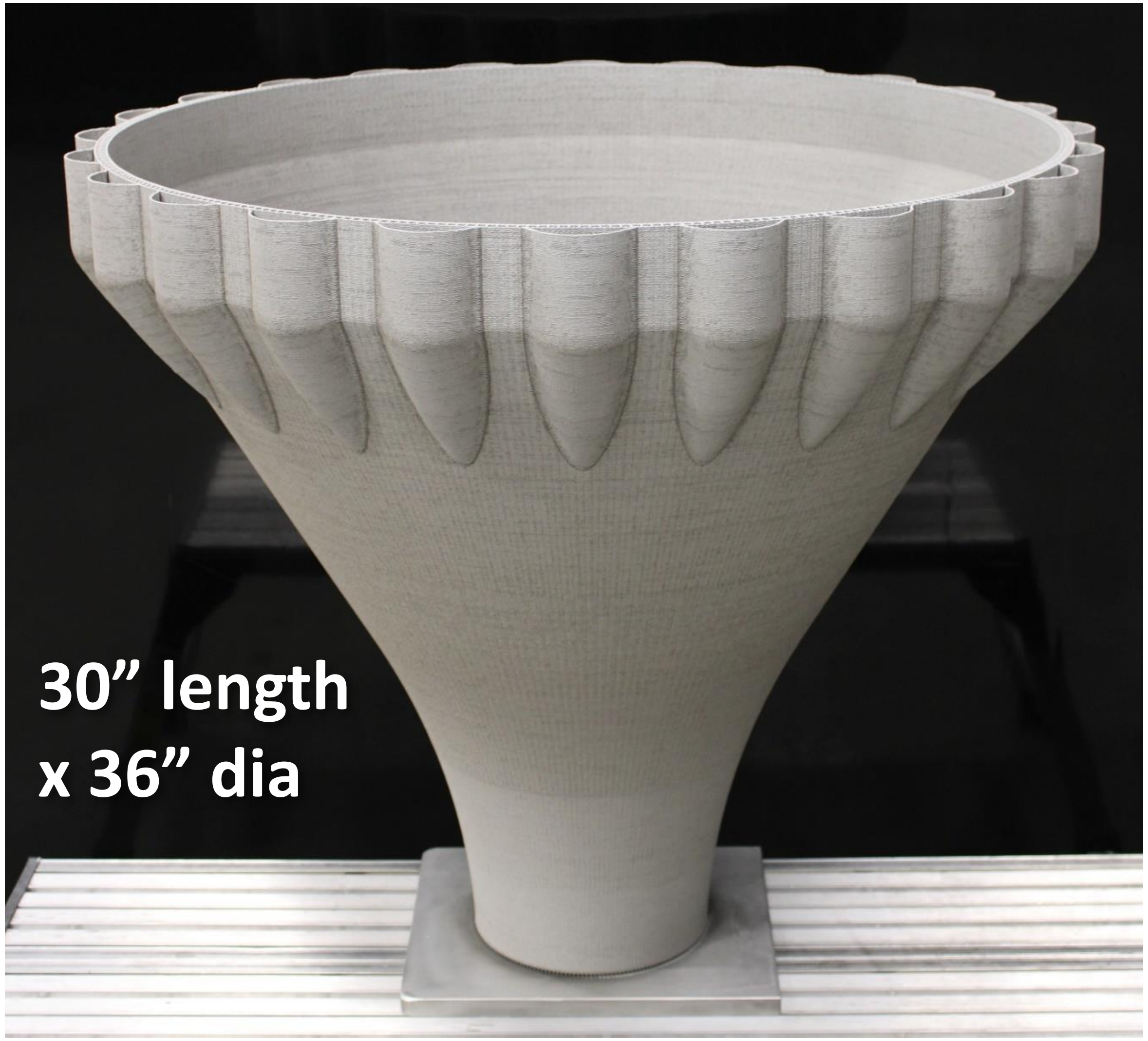
Reference: P.R. Gradl, T.W. Teasley, C.S. Protz, C. Katsarelis, P. Chen, Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications, in: AIAA Propuls. Energy 2021, 2021: pp. 1–23. https://doi.org/10.2514/6.2021-3236.

Demonstrator Aerospike LP-DED Nozzle



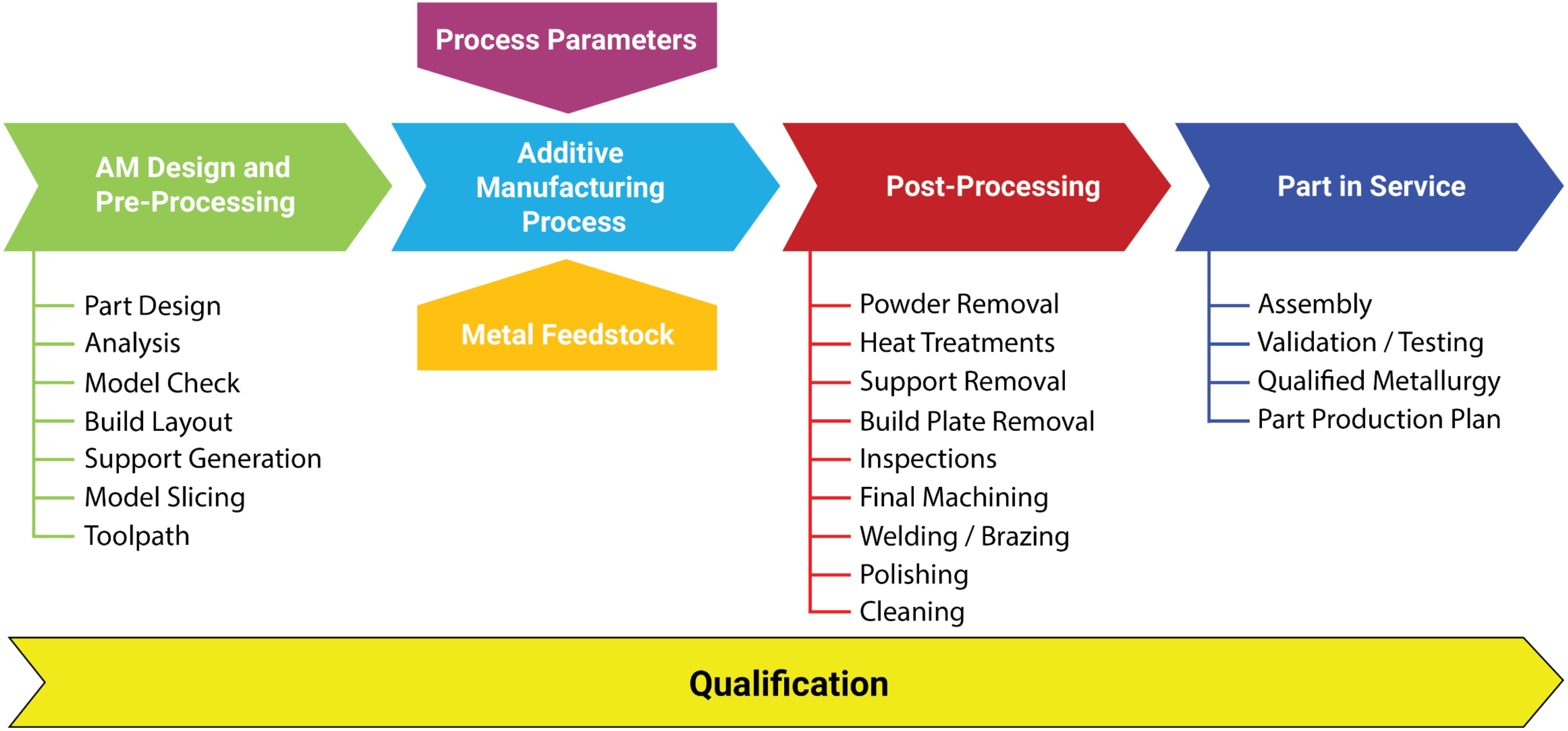


LP-DED Aluminum 6061-RAM2



30” length
x 36” dia

Additive Manufacturing Typical Process Flow

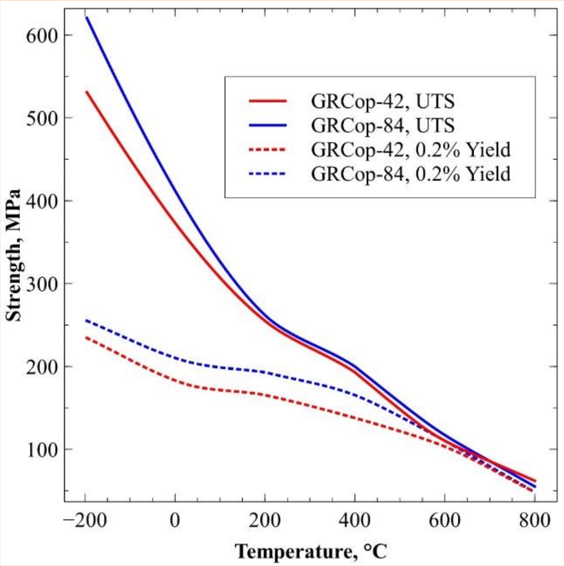


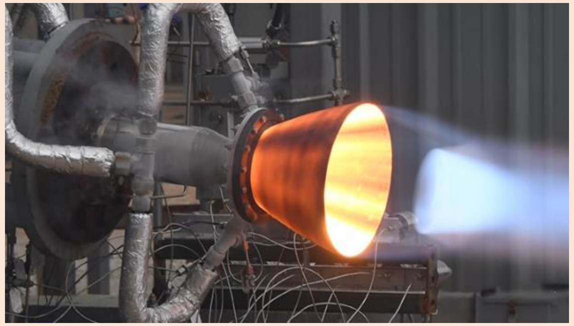
Proper AM process selection requires an integrated evaluation of all process lifecycle steps

Reference: Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

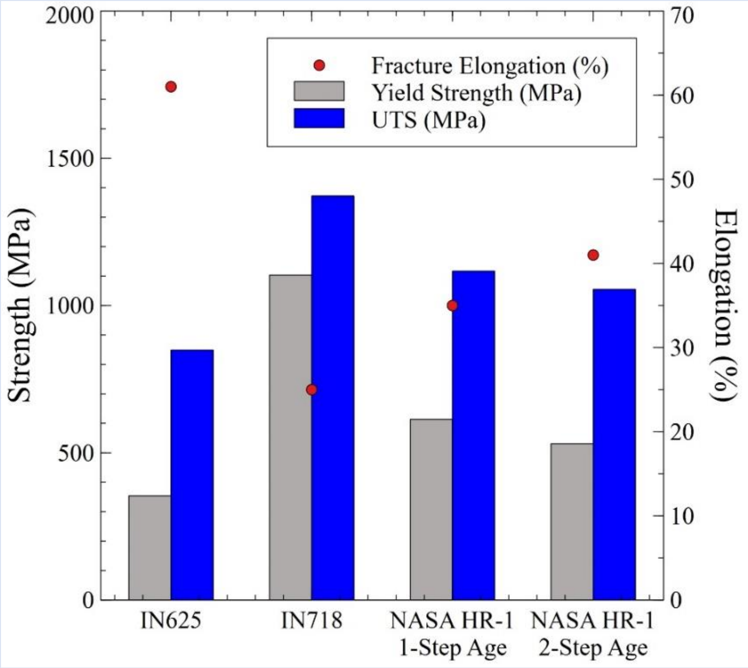
AM Enabling New Alloy Development

GRCop-42, High conductivity and strength for high heat flux applications

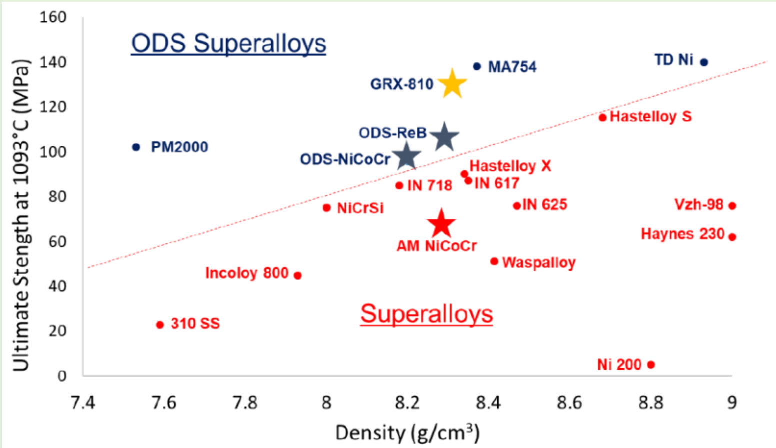




NASA HR-1, high strength superalloy for hydrogen environments

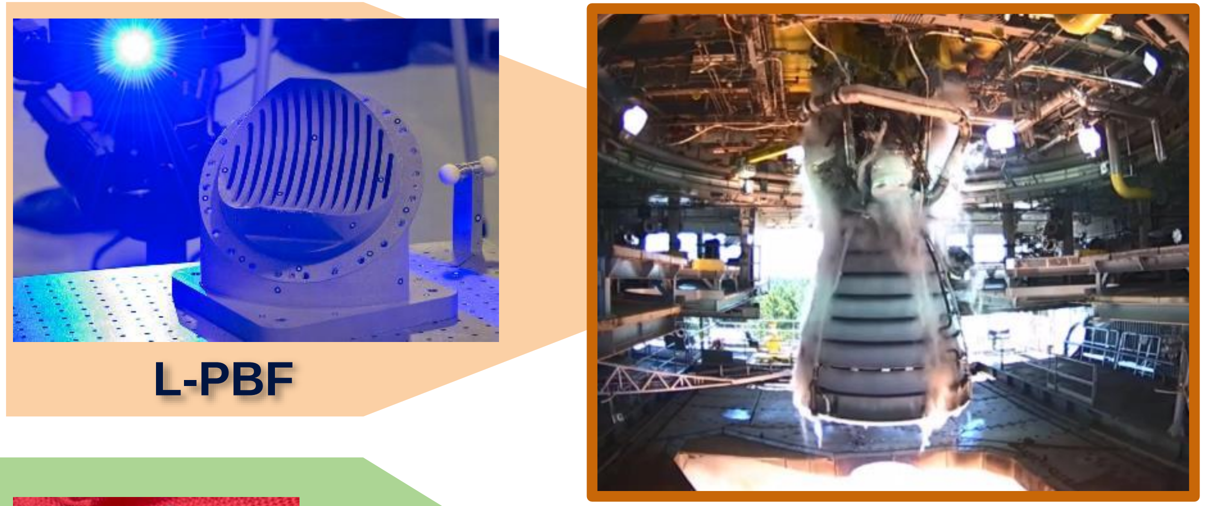


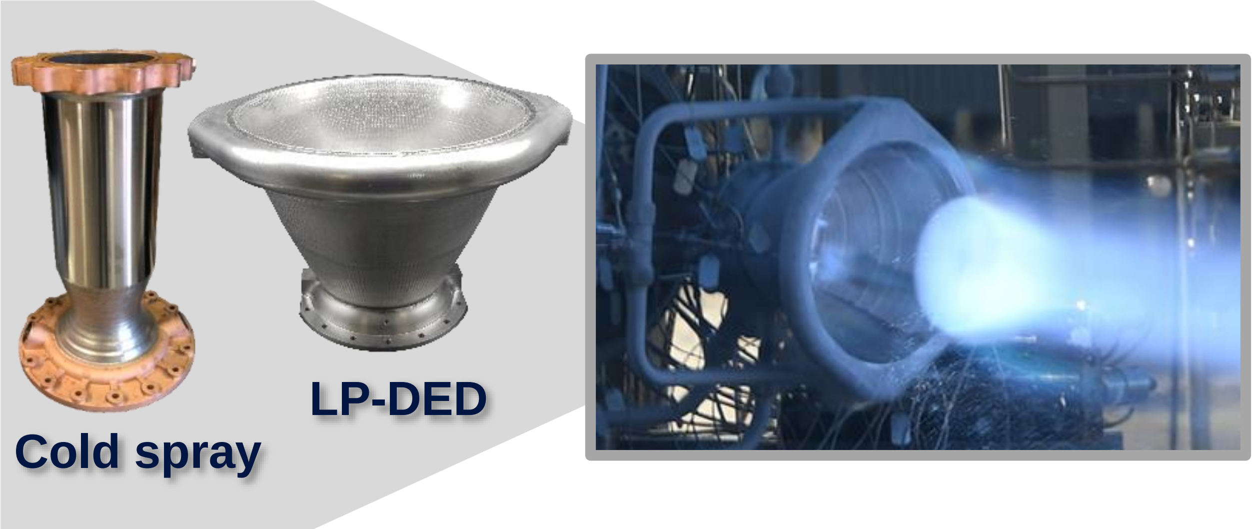
GRX-810, high strength, low creep rupture and oxidation at extreme temperatures

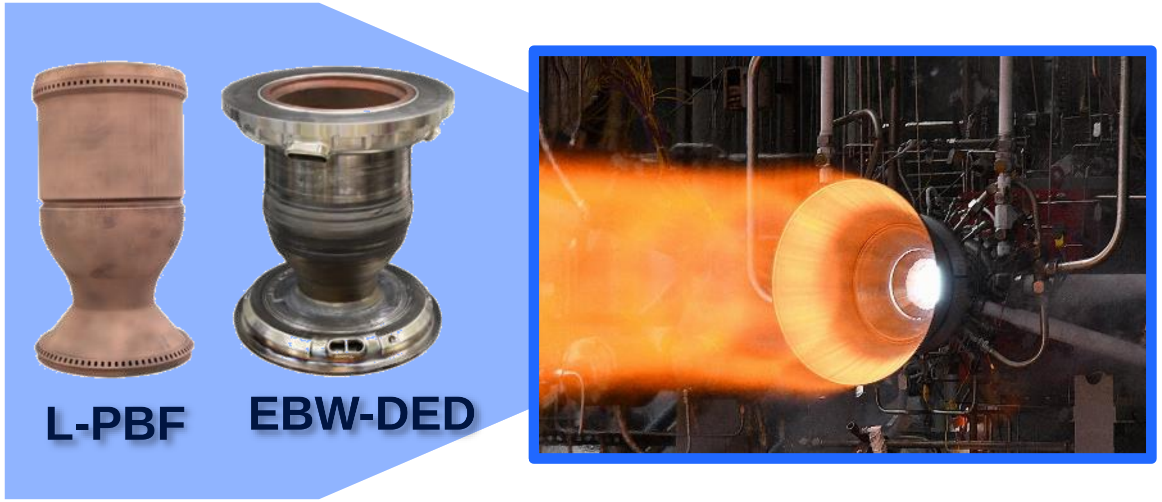


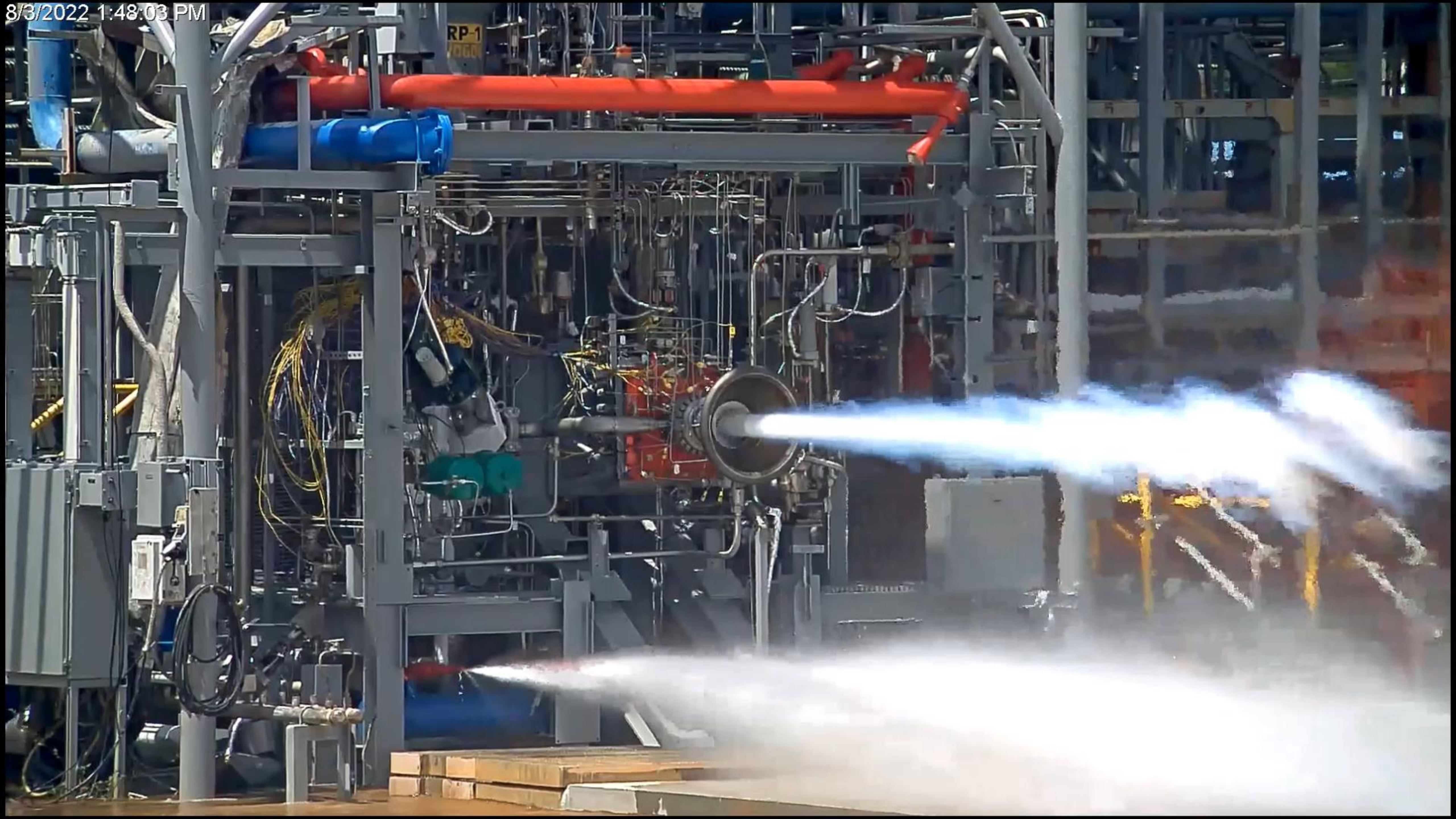
Ref: Tim Smith, Christopher Kantzos / NASA GRC

Industrial Maturity and TRL of AM Processes








8/3/2022 1:48:03 PM
RP-1

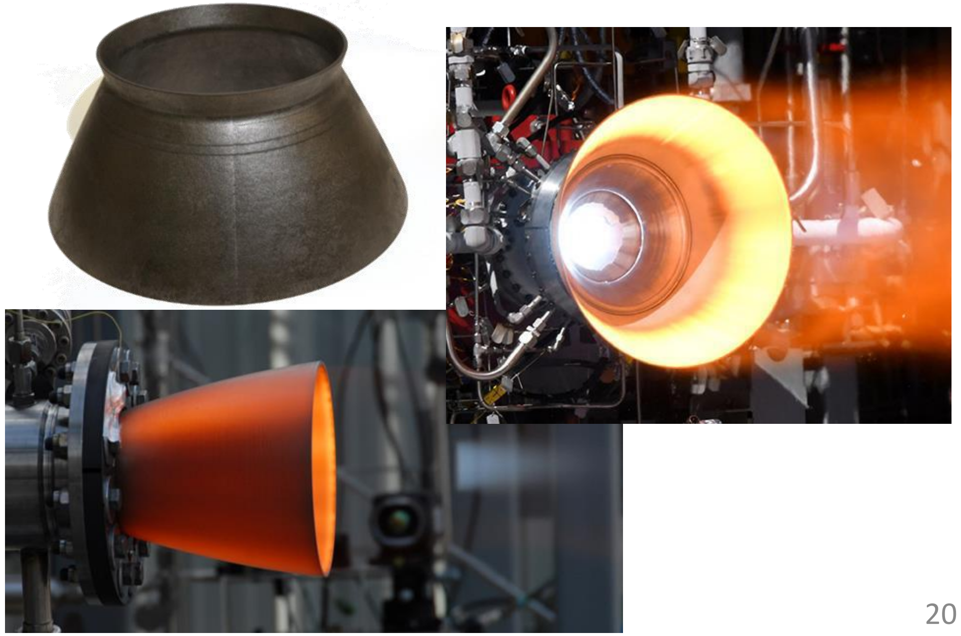
Carbon-Carbon (C-C) and Carbon Matrix Composite (CMC) High Temp Nozzles

- CNE characterization and material property database development using tag-end rings
  - Nondestructive characterization at MSFC: infrared thermography (IRT) & computed tomography (CT)
  - Mechanical & thermal testing at Southern Research: material properties, sub-element hoop tension tests
  - Tag-ends taken from CNE’s for 1.2K-lbf and 35K-lbf engine tests. Provided by: Allcomp, C-CAT, & NGIS

- Materials screening via 1.2K-lbf LOX/GH2, LOX/LCH4, LOX/RP-1 engine testing
  - Investigating coatings, composite matrix chemistry, & attachment concepts
  - Nozzle extensions supplied by: Allcomp, C-CAT, NGIS, PSI

- Mid-scale demonstration via META4X4 7K-lbf LOX/LCH4
  - Completed for lander-class engines

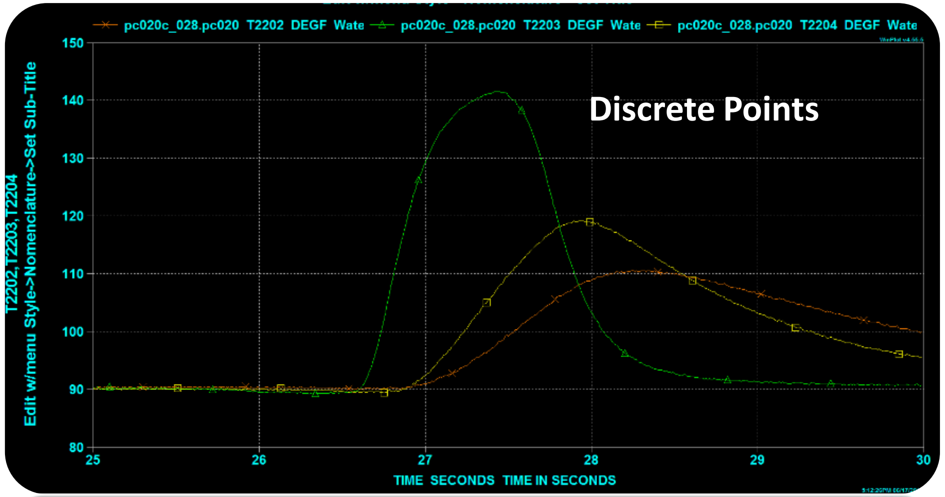
- Large-scale demonstration via 35K-lbf LOX/LH2
  - Performed two low-budget feasibility/demonstration
  - Test series with PAN- & lyocell-based C-C

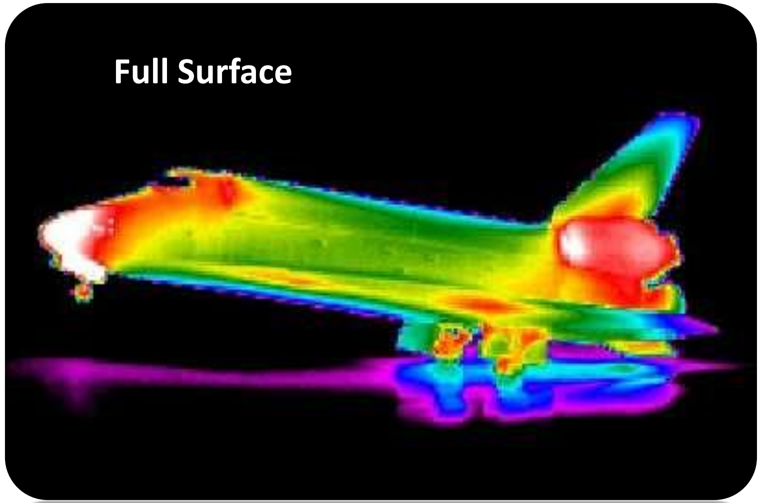


Optical Techniques for Measurements

- Subscale and Full-scale testing requires expensive and labor intensive instrumentation to better understand hardware performance
  - Design Modifications and Performance Predictions based on “discrete” point instrumentation
    - Thermocouples, Pressure Transducers, Accelerometers, Strain Gages
- **Challenge: Measure highly dynamic elevated temperature components**

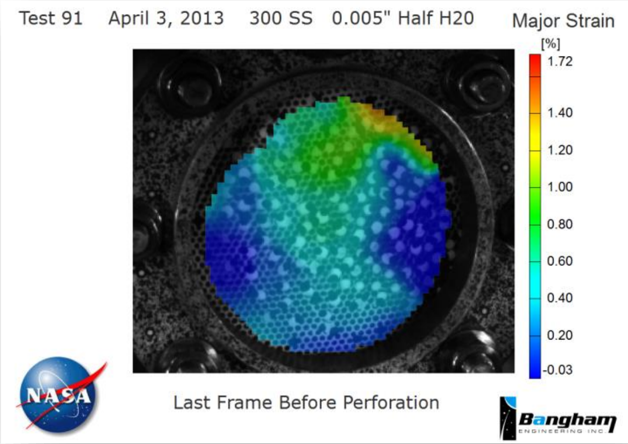
Full Surface > Point
IR > Thermocouple
D.I.C. > Strain Gage



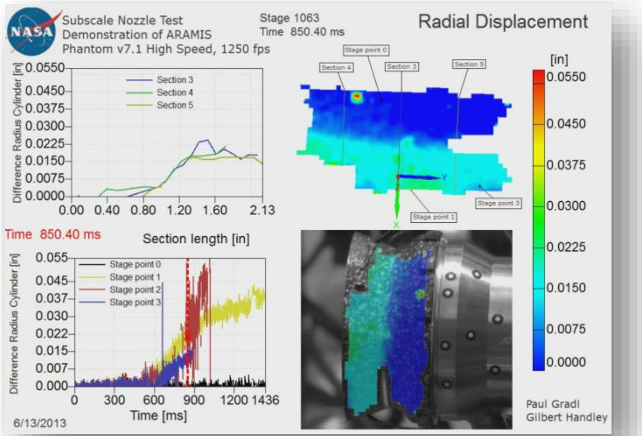


Goal: Augment Traditional Gages to gain a better understanding of hardware and environment loads to design more efficient components and systems

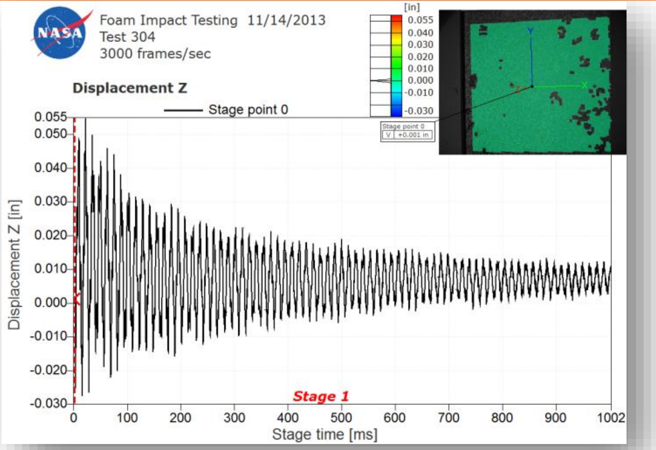
Applications of Digital Image Correlation (DIC) for Rocket Applications



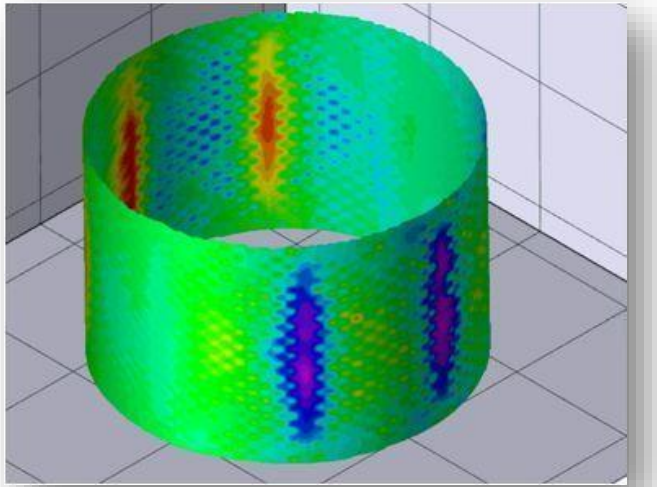
Blast Pressure Wave Tracking at 70,000 fps



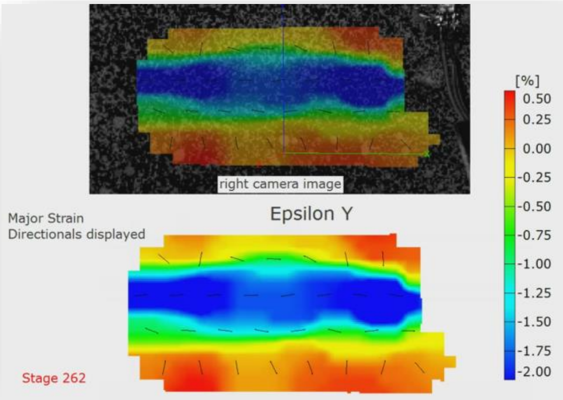
Subscale Nozzle Displacements at 1700F



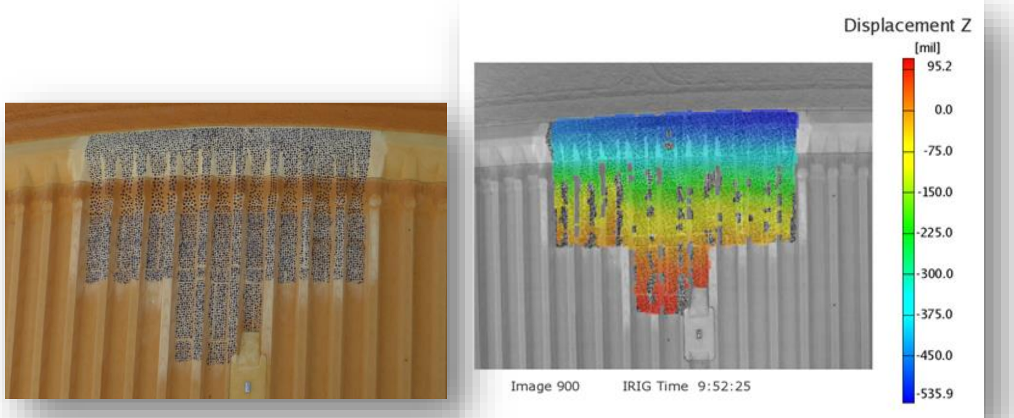
Debris Impact Testing – Eliminated Strain Gages



Full-Field Strain and Displacements of 18-ft Dia Tank



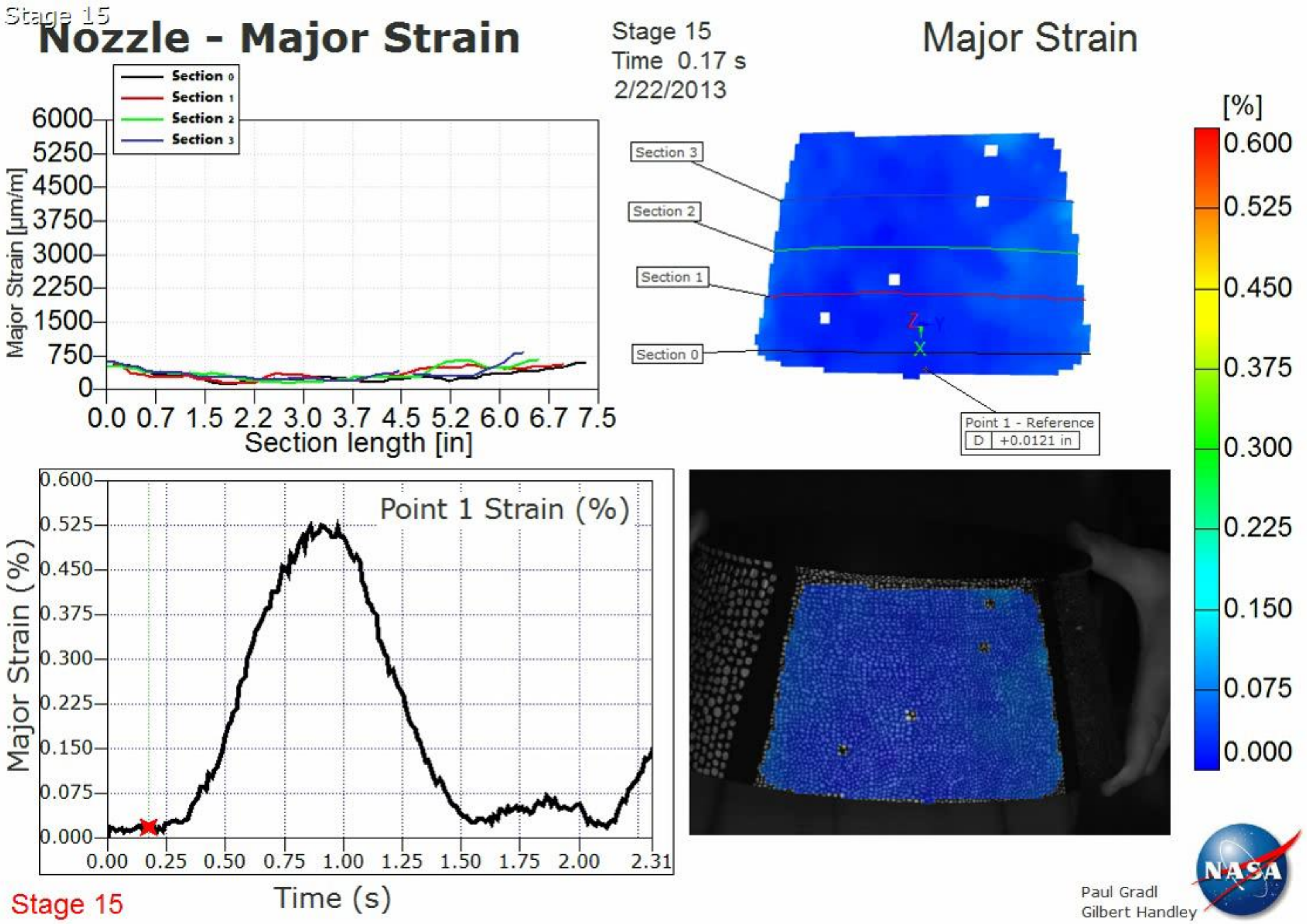
High Speed Composite Compression – Direct Application of Major Strain



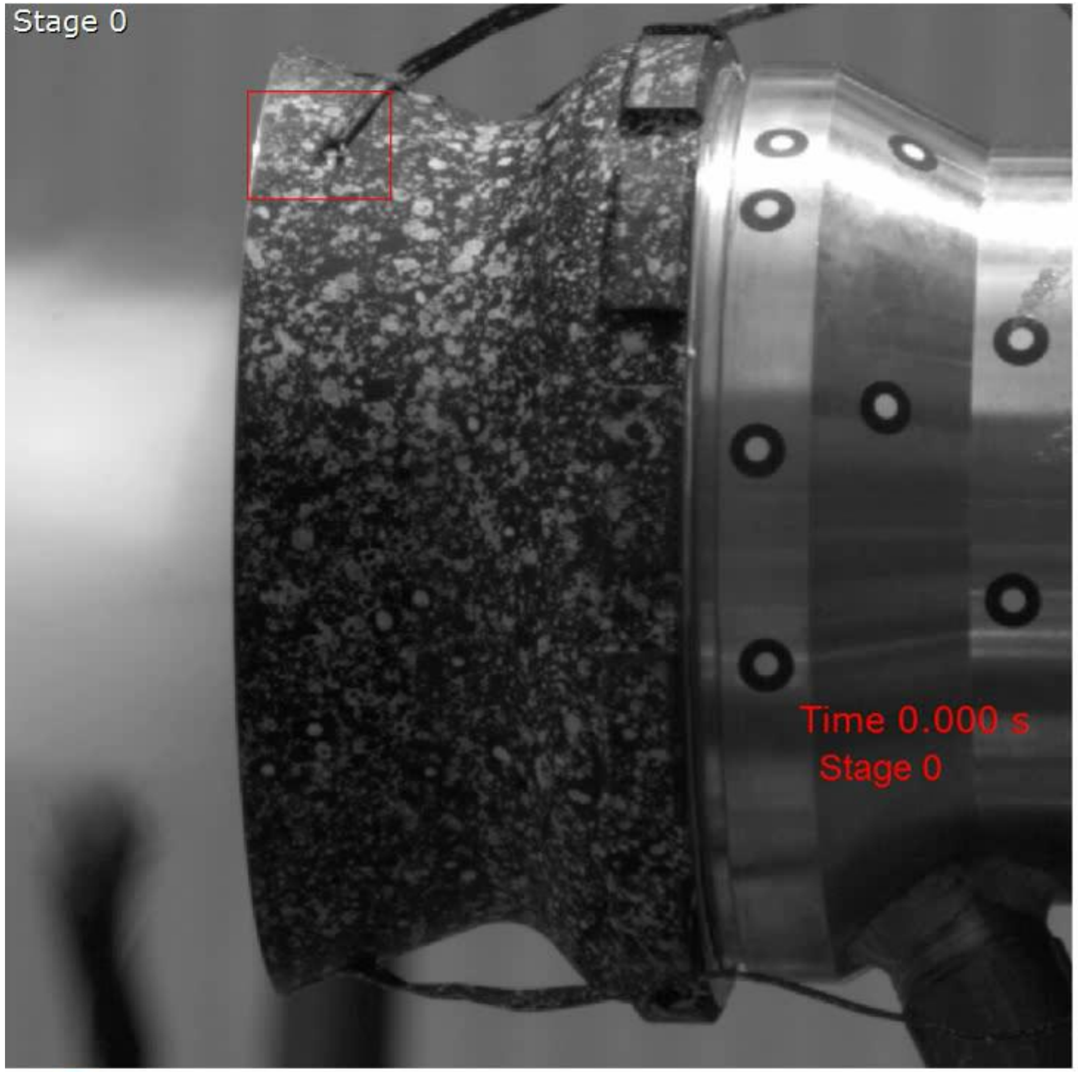
ET (on Pad) Cryo tanking test to observe stringer displacement

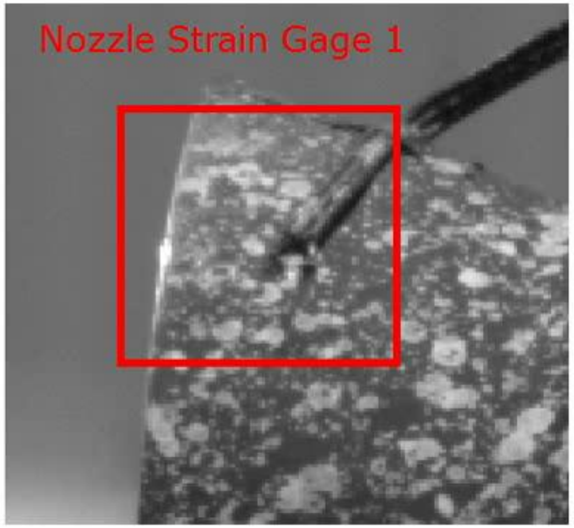
Ref: Todd Boles, MSFC/ET30

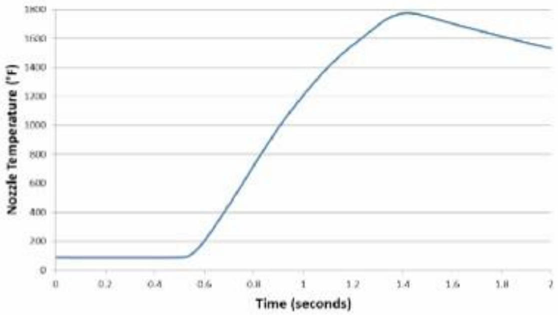
Tracking Real-time strain on hardware



Tracking Strain using DIC at high temperatures on rocket nozzles





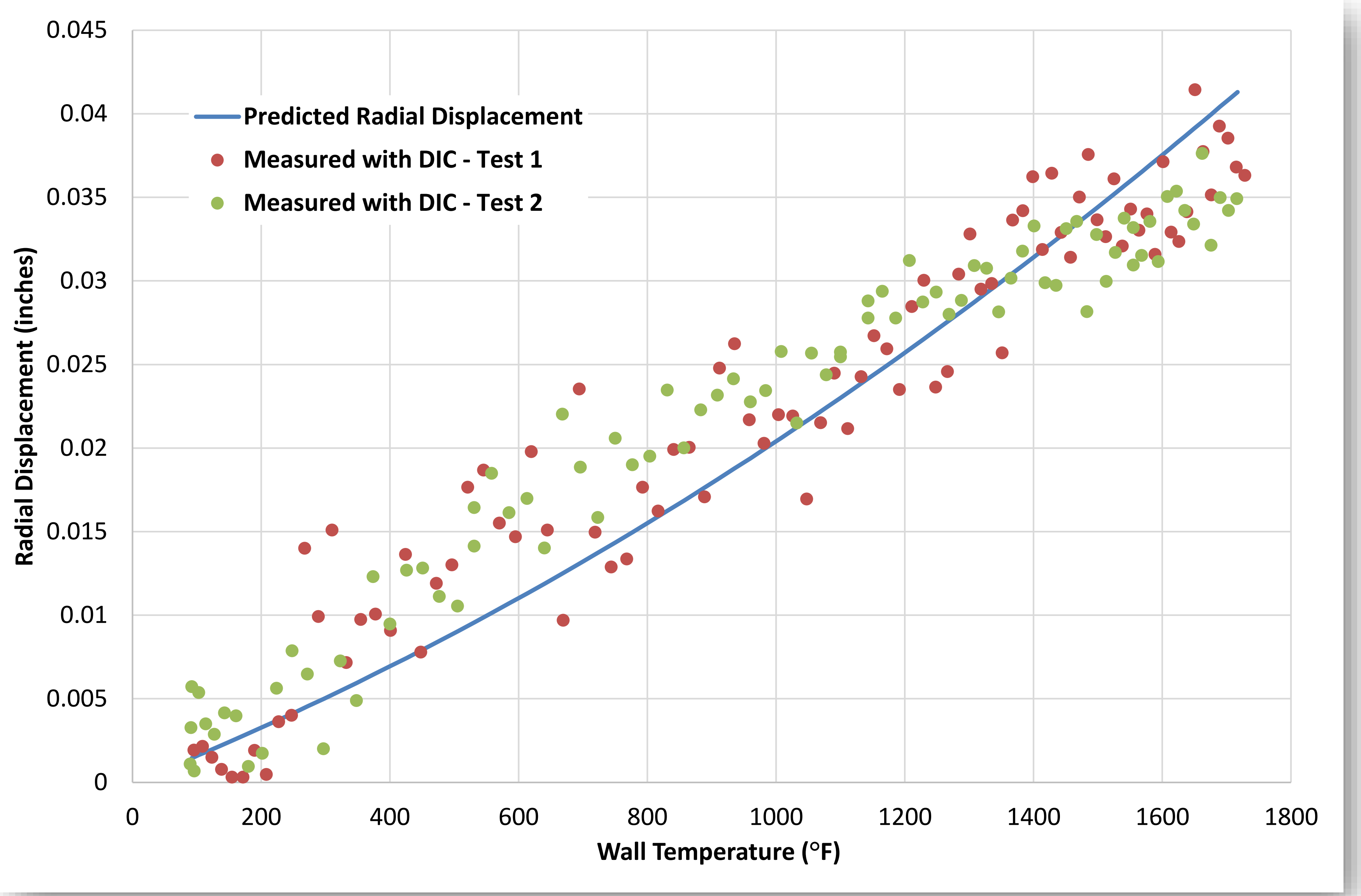


Subscale Nozzle Hotfire Demonstration
Phantom v7.1 M, 1250 fps

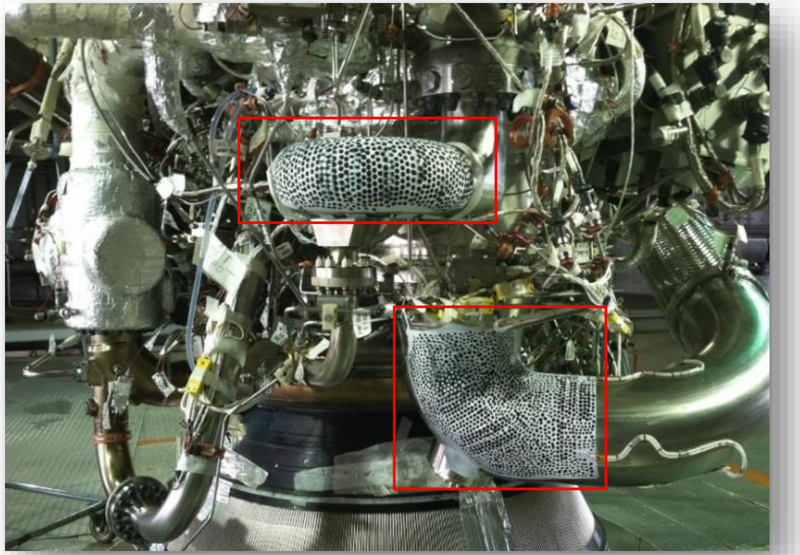
6/13/2013

Paul Gradl
Gilbert Handley

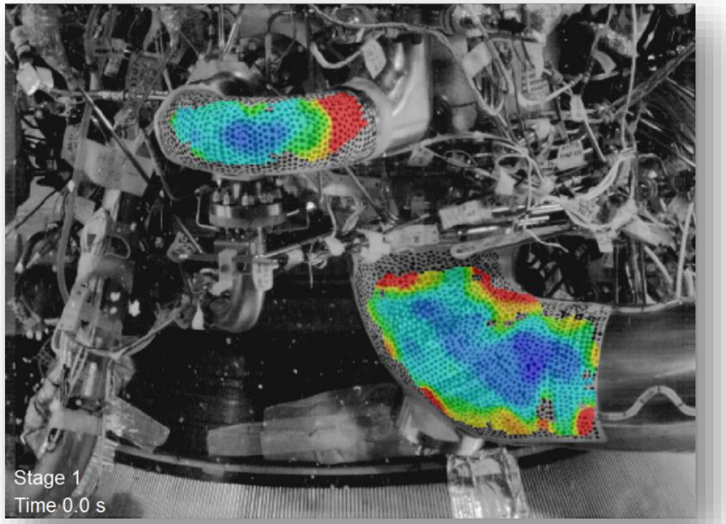
Subscale Hotfire Testing – Data Analysis



Digital Image Correlation for Full Scale Rocket Engine Testing

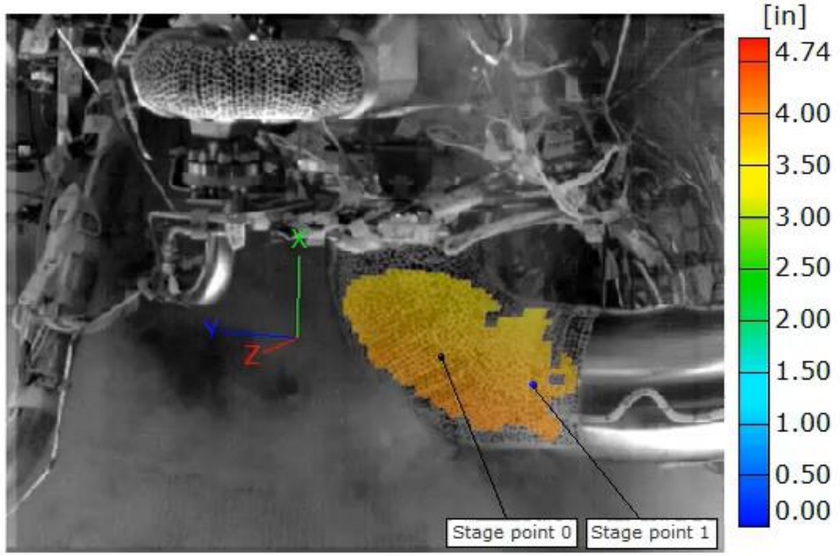


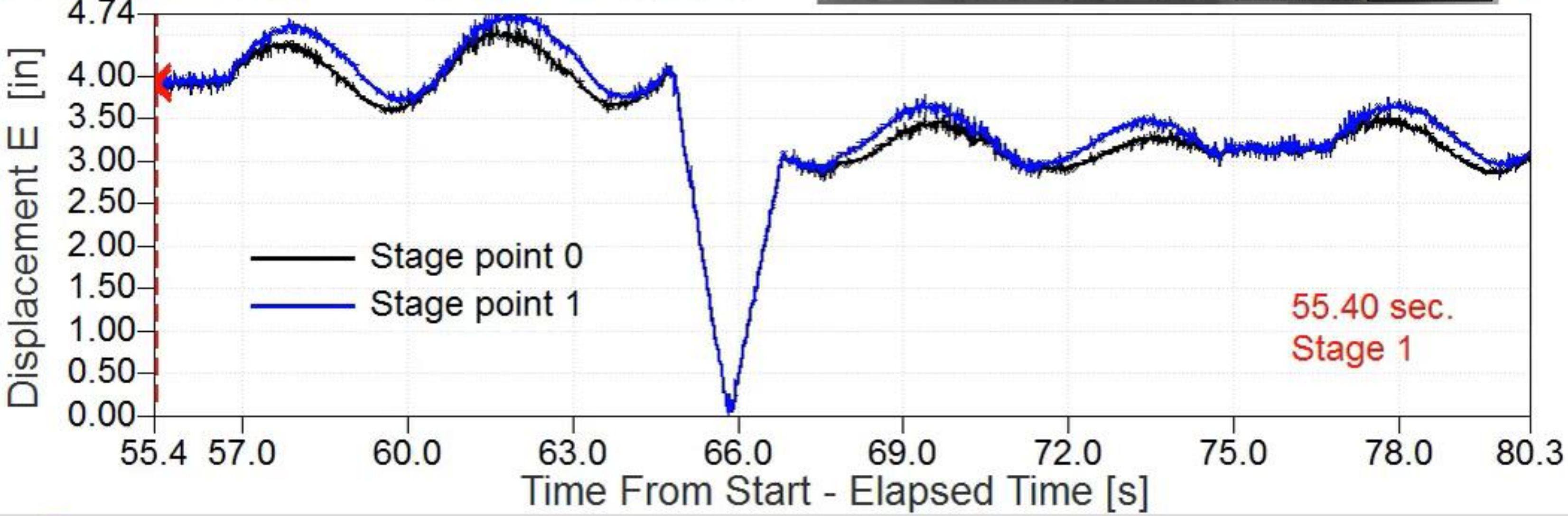
Stereo Cameras installed and Speckle Pattern Applied at Stennis A1 Stand



High speed cameras for DIC

Results from Full Scale Engine Testing





ARAMIS Trial on J-2X A1J028

Paul Gradl
Gilbert Handley

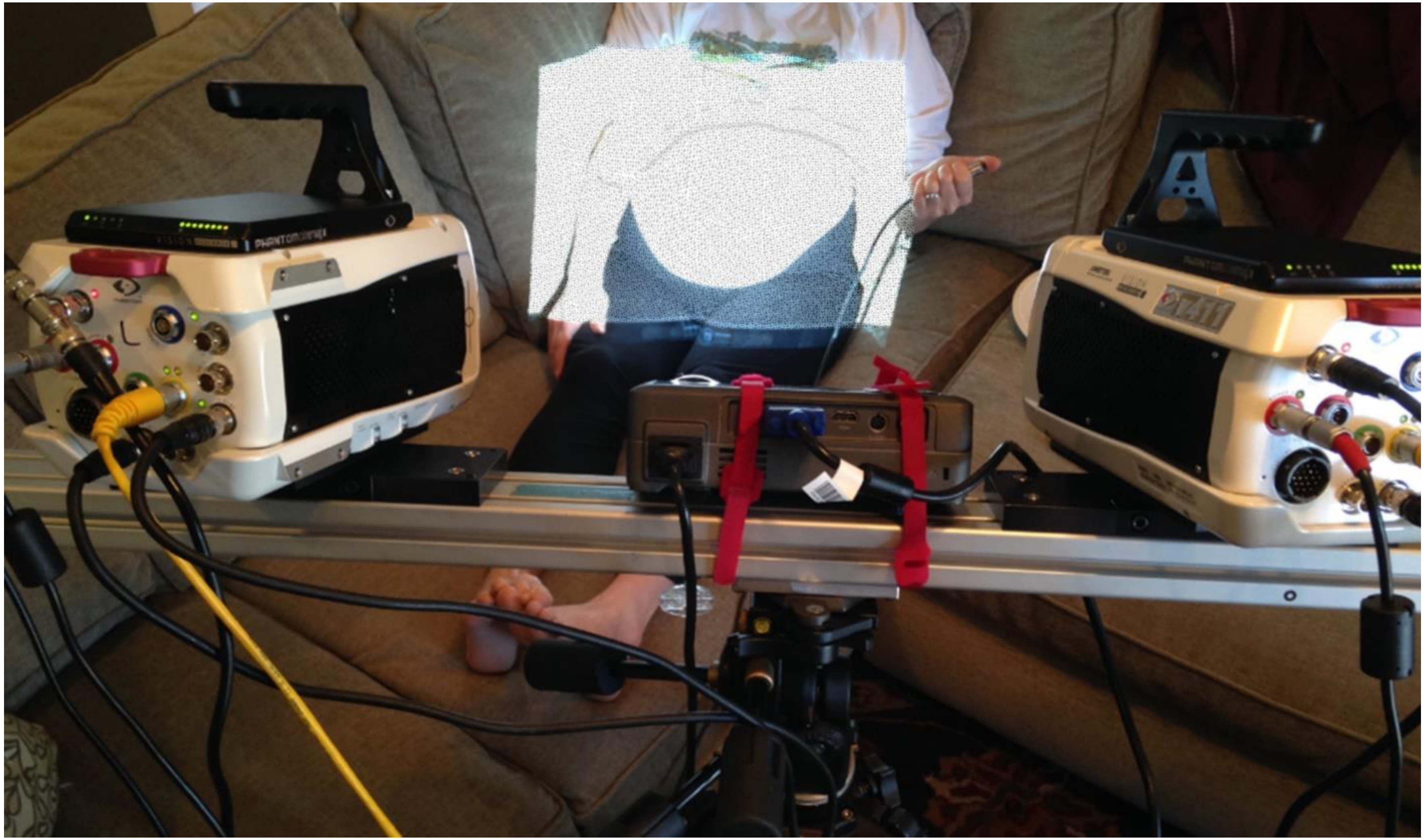
Displacement E (Total X, Y, Z)

Optical Measurements…

Dynamic responses require an input to excite the system…

Non-contact Optical Measurements

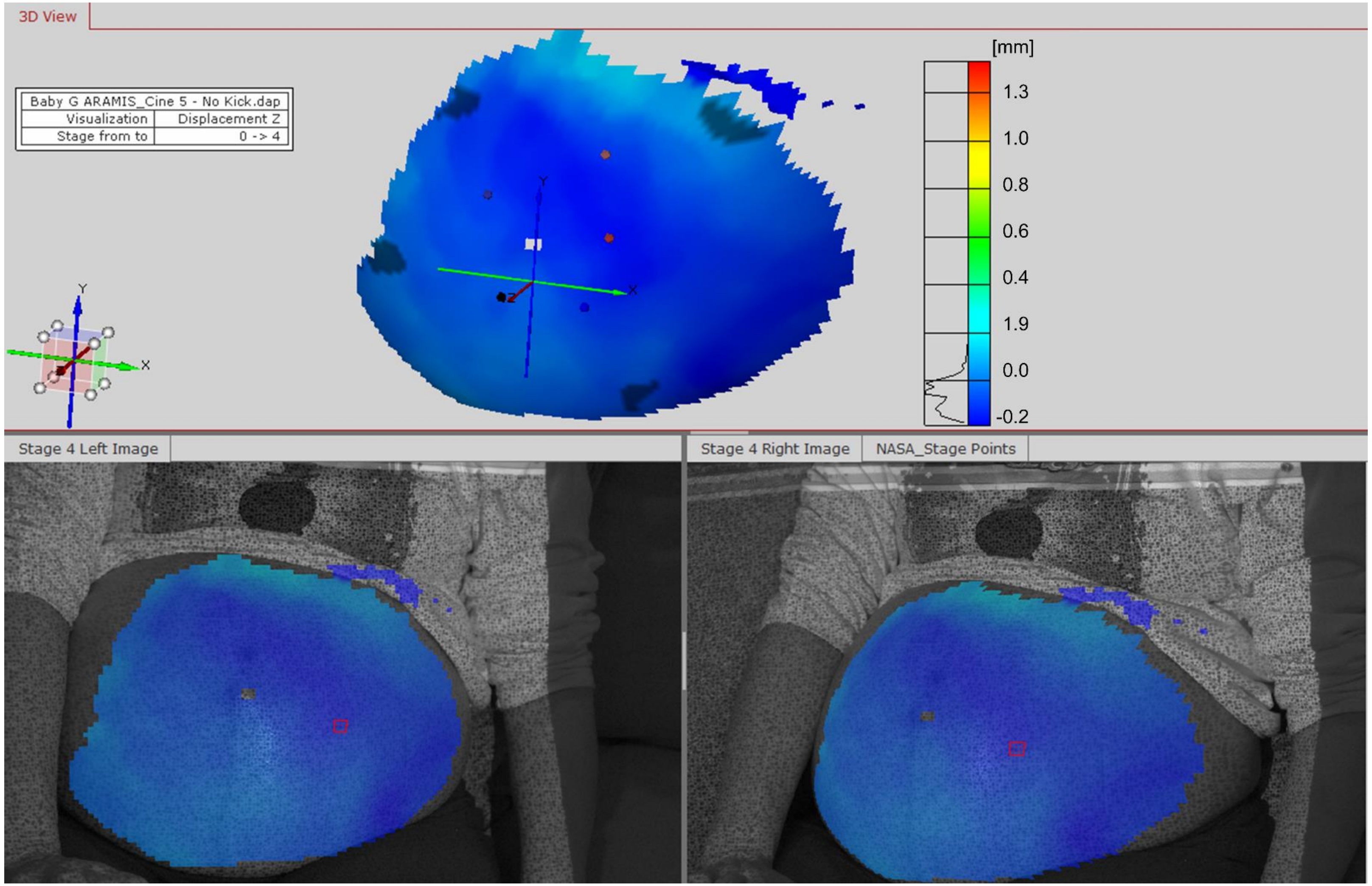
Images were collected using a projected pattern instead of painting a speckle pattern on her belly… High Speed cameras were post triggered after movements felt.



Gradl, P.R., 2022. Application of optical measurement techniques during various stages of pregnancy. Measurement: Sensors 24, 100453. https://doi.org/10.1016/j.measen.2022.100453

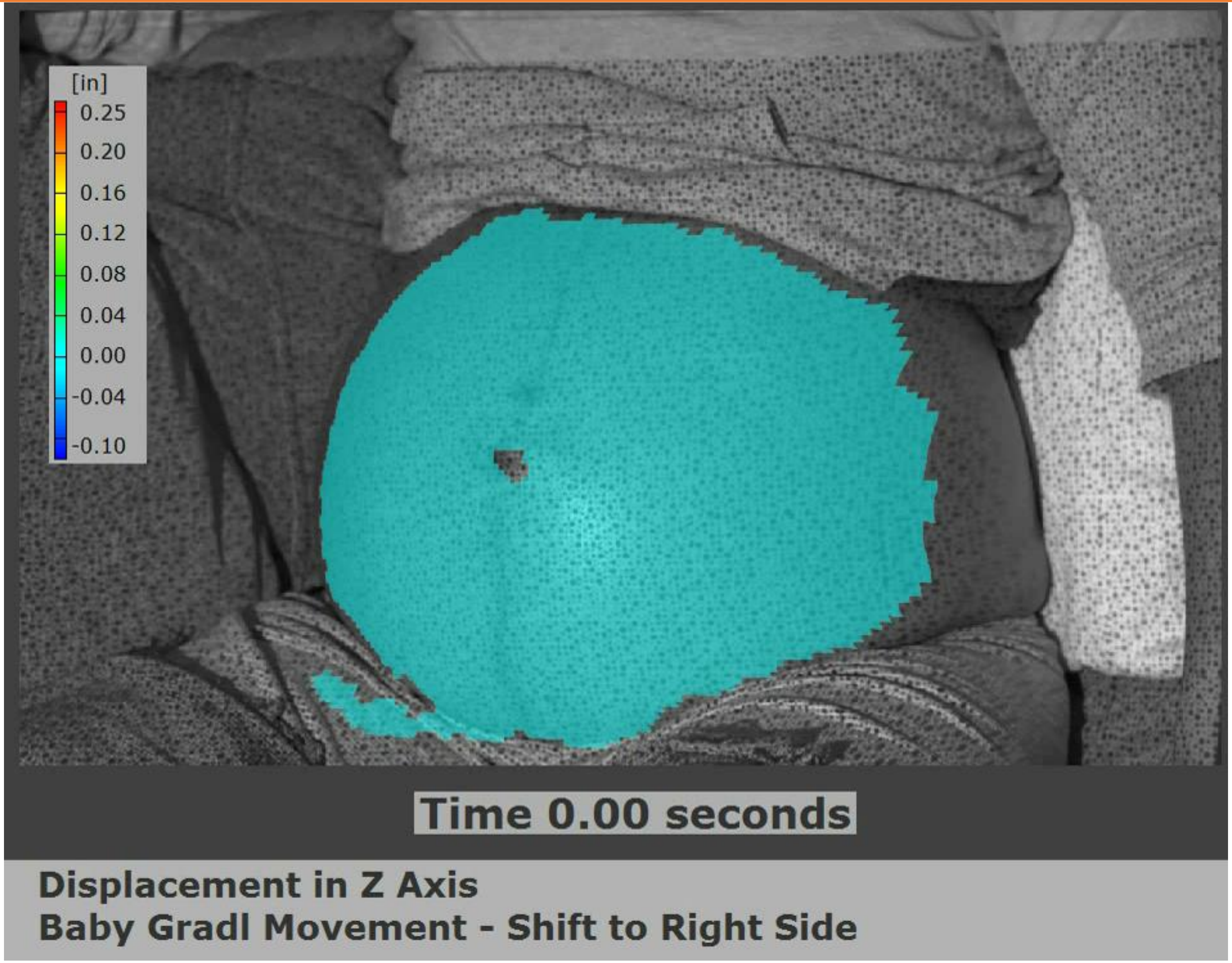
Non-contact Optical Measurements

To ensure that kicks and movement data was real a background test was conducted with no baby movement (to correct for breathing and body motion)



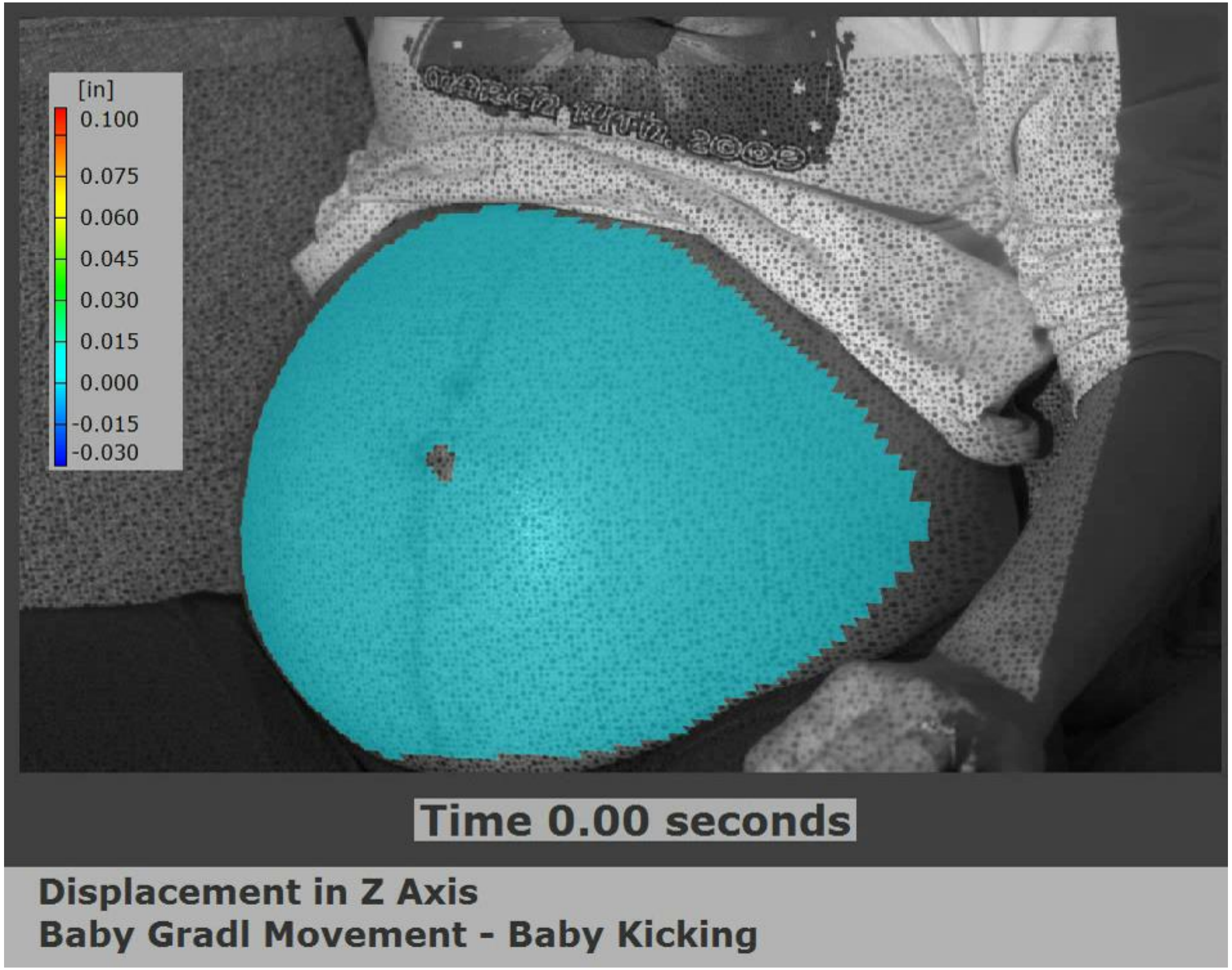
Gradl, P.R., 2022. Application of optical measurement techniques during various stages of pregnancy. Measurement: Sensors 24, 100453. https://doi.org/10.1016/j.measen.2022.100453

Non-contact Optical Measurements



Gradl, P.R., 2022. Application of optical measurement techniques during various stages of pregnancy. Measurement: Sensors 24, 100453. https://doi.org/10.1016/j.measen.2022.100453

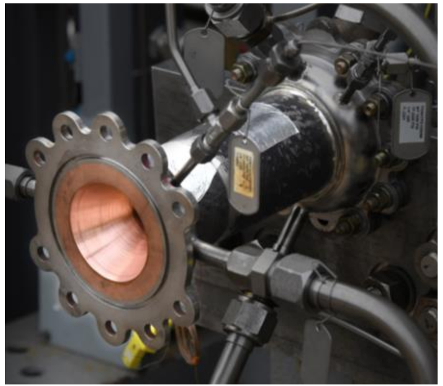
Non-contact Optical Measurements



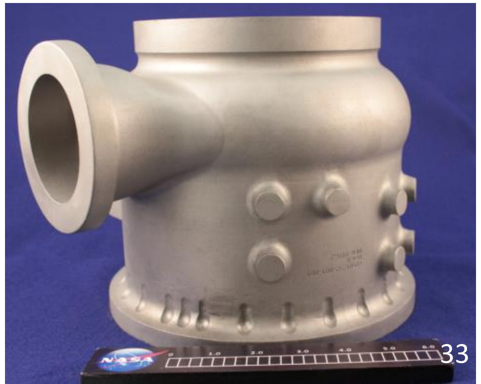
Gradl, P.R., 2022. Application of optical measurement techniques during various stages of pregnancy. Measurement: Sensors 24, 100453. https://doi.org/10.1016/j.measen.2022.100453

Summary

- Various advanced manufacturing and AM processes have matured for rocket propulsion applications each with unique advantages and disadvantages.
- AM is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense.
- **Complete understanding of the design process, build-process, feedstock, and post-processing is critical to take full advantage of AM.**
- Additive manufacturing takes practice!
- Standards and certification of the AM processes are in-work.
- AM is evolving and imagination is the limit.





Contact:
Paul Gradl
NASA MSFC
Paul.R.Gradl@nasa.gov

Photo: NASA/Ben Smegelsky

NASA led book on Metal Additive Manufacturing

https://arc.aiaa.org/doi/book/10.2514/4.106279

Online version and hardcopy available

P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022). *Metal Additive Manufacturing for Propulsion Applications*. AIAA Progress in Astronautics and Aeronautics Book Series. https://arc.aiaa.org/doi/book/10.2514/4.106279

Additive manufacturing (AM) processes are proving to be a disruptive technology and are grabbing the attention of the propulsion industry. AM-related advancements in new industries, supply chains, design opportunities, and novel materials are increasing at a rapid pace. The goal of this text is to provide an overview of the practical concept-to-utilization lifecycle in AM for propulsion applications.